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# THE EFFECT OF FULLY ANOXIC CONDITIONS AND FREQUENCY OF EXPOSURE TO ANOXIC AND AEROBIC CONDITIONS ON THE GROWTH OF LOW F/M FILAMENTS IN NITROGEN REMOVAL SYSTEMS

by
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## DECLARATION

I, DAVID ANDREW KETLEY
Hereby declare that this thesis is my own
work and has not been submitted for a degree
at another University

Signed by candidate

September 1991

# SYNOPSIS

Filamentous bulking, caused predominantly by low F/M filaments (Blackbeard *et al*, 1986, 1988), results in considerable settling problems in full scale nitrogen (N) and nutrient (N & P) removal activated sludge plants in South Africa. The development of specific methods for control of low F/M filaments in these plants would lead to significant savings because higher flows and loads could be treated in existing plants. From the findings of Blackbeard *et al* (1986, 1988) an extensive research project was undertaken by Gabb *et al* (1989a) into specific control of low F/M filament bulking. This project investigated the effectiveness of selectors, the proposed method of low F/M filamentous bulking control and found them to be ineffective. Consequently a second comprehensive laboratory research investigation was commenced in 1989. The work presented in this thesis forms a part of this investigation; the experimental investigation was conducted in 3 phases investigating

(1) the effect of fully anoxic conditions and low nitrate concentrations during the anoxic phase of an intermittent aeration cycle on low F/M filament growth in continuously fed completely mixed single reactor systems receiving a synthetic sewage feed

(2) the effect of fully anoxic conditions on low F/M filament growth in continuously fed completely mixed single reactor systems receiving real sewage

(3) the effect of alternating the frequency of exposure of low F/M filaments to anoxic/aerobic conditions (i.e. increasing the length of the aeration cycle but maintaining the aerobic mass fraction) in intermittently aerated continuously fed single completely mixed reactor systems receiving real sewage.

In phase 1 two continuously fed single completely mixed reactor systems were operated: system CFR 1, a control intermittently aerated system operated with short aeration cycles (up to 30 minutes per cycle with a dissolved oxygen (DO) concentration up to 3.0mgO/l), and system ANOX 1, a fully anoxic system. Both systems were fed a synthetic sewage developed by Gabb *et al* (1989a) (but not reported by them) and Casey *et al* (1990). In CFR 1 no nitrate was dosed to the system to induce low nitrate concentrations in the anoxic period of the aeration cycle and the DSVI decreased from above 150ml/g to below 80ml/g. Operational

problems were encountered as a result of production of polymeric material which caused coagulation of the sludge flocs into large clumps leading to blockages. The reason for the production of the polymeric material is unknown. Neither nitrate dosing nor seeding with a low F/M filament bulking sludge improved the sludge quality. Despite the poor sludge quality, the sludge settleability was good and the DSVI remained below 100ml/g. From this it was concluded that in intermittently aerated single reactor systems receiving the synthetic sewage as feed, low nitrate concentrations during the anoxic period lead to amelioration of low F/M filament bulking caused by the filaments 1851 and 1701 and low DSVI values. The production of polymeric material could have played a role in the reduction of the DSVI.

In the fully anoxic system ANOX 1 the DSVI decreased initially from about 250ml/g to 130ml/g by day 24, caused by the decline of filament type 1701 and all low F/M filaments except *Haliscomenobacter hydrossis*. From day 24 *H.hydrossis* caused an increase in DSVI to above 200ml/g for the remainder of the phase 1 period. In ANOX 1 low F/M filaments like 0092, 0041 and 0803 either disappeared from the system or were present at a tertiary level but were unable to proliferate under the fully anoxic conditions and did not contribute to bulking. Reduced nitrate dosing to ANOX 1 for 10 days led to an explosive proliferation of *H.hydrossis* and a dramatic increase in the DSVI to 400ml/g. When high nitrate dosing was reestablished, the DSVI decreased to a comparatively low value but remained above 200ml/g for the remaining 65 days of the experimental period.

From phase 1 it was concluded that under fully anoxic conditions with synthetic sewage feed, only *H.hydrossis* was able to proliferate to the extent of causing bulking; other low F/M filaments were able to grow in the system but not to the extent of causing bulking. As *H.hydrossis* is a filament of little consequence in low F/M bulking in systems fed real sewage it was decided to feed the fully anoxic system with real domestic sewage to examine the effect of fully anoxic conditions on the low F/M filaments other than *H.hydrossis*.

In phase 2, two fully anoxic continuously fed single completely mixed reactor systems, ANOX 2 and ANOX 3, both identical to ANOX 1, were operated receiving real raw sewage. Sufficient nitrate was dosed to the systems to ensure anoxic conditions. The DSVI of both systems, started up with totally different low F/M filament populations, showed a rapid decrease from 250ml/g and 180ml/g for

ANOX 2 and 3 respectively to less than 80ml/g. It was concluded from these observations that low F/M filaments were unable to proliferate to the extent of causing bulking in fully anoxic continuously fed single completely mixed reactor systems fed real sewage. It was also concluded that the excessive growth of *H.hydrossis* observed in ANOX 1 was attributable to the synthetic sewage feed and was not a true reflection of that filament's growth under the same conditions when fed real sewage.

Because neither fully anoxic nor fully aerobic (after Gabb *et al*, 1989a) conditions support low F/M filaments it was proposed that if the low F/M filaments were exposed to long periods of anoxic and aerobic conditions, thereby decreasing the frequency of alternating anoxic and aerobic conditions, then the filaments may behave similarly to that observed in the respective fully anoxic or aerobic conditions and bulking may be ameliorated. Accordingly phase 3 of the investigation was initiated using intermittently aerated systems but reducing progressively the frequency of alternation between anoxic and aerobic conditions.

In phase 3 two intermittently aerated continuously fed single completely mixed reactor systems, CFR 2 and CFR 3, were operated receiving real sewage feed. A 30% aerobic mass fraction was maintained because it was found that this best promoted low F/M filament proliferation. The frequency of alternation of anoxic and aerobic conditions was varied from 48 cycles/d to 1 cycle every 3 days with intermediate frequencies of 3 cycles/d, 2 cycles/d and 1 cycle/d.

All the intermittent aeration cycles imposed on CFR 2 and CFR 3 caused low F/M filament proliferation with the DSVI increasing in all cases to over 400ml/g whether the aeration cycle was imposed on the system at a low (less than 150ml/g) or a high (greater than 200ml/g) DSVI. When the DSVI increased to around 400ml/g settler failure occurred and the systems were continuously aerated to reduce the DSVI before reimposing an intermittent aeration regime. In each case of continuous aeration a rapid reduction in DSVI was observed. If the DSVI was less than 150ml/g when the intermittent aeration cycle was reimposed then the increase in DSVI was slower than if the same aeration regime was imposed at a higher DSVI.

The filament populations in CFR 2 and 3 during phase 3 showed gradual changes over long periods of time with none of the changes observed being directly attributable to a particular aeration pattern. From startup type 021N became

dominant in both systems and remained dominant until day 102. By day 43 *Microthrix parvicella* had appeared in the systems and increased in status until it became dominant in both systems by day 133, remaining dominant in both CFR 2 and CFR 3 until day 190, just prior to imposing the frequency of once per 3 days on the systems. On day 216, when the once per 3 day frequency experiment ended, type 0803 had become dominant in CFR 2 and *M.parvicella* was still dominant in CFR 3 giving no clear indication of which filaments favour this aeration regime. From phase 3 it was concluded that frequency of alternation of anoxic and aerobic conditions in intermittently aerated continuously fed single completely mixed reactor systems had no effect in reducing bulking caused by low F/M filaments.

At the end of the phase 3 experimental period CFR 2 was switched to fully anoxic operation and CFR 3 to fully aerobic operation. Both of these operational regimes led to amelioration of the low F/M filament bulking in the systems with the DSVI values decreasing from 300ml/g to 100ml/g in CFR 2 and from around 400ml/g to less than 80ml/g in CFR 3. After exposure to fully anoxic conditions 0092 was dominant in CFR 2 showing that this filament could grow better than other low F/M filaments such as *M.parvicella* under these conditions but not to the extent of causing bulking. This confirmed the earlier observations that fully anoxic and fully aerobic operation of the systems is effective in ameliorating low F/M filament bulking with continuous aeration leading to more rapid decreases in DSVI than fully anoxic operation.

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# CHAPTER 1

# INTRODUCTION

Filamentous bulking is a considerable problem in nutrient removal activated sludge plants in South Africa. This type of bulking (as opposed to non filamentous bulking caused by the overproduction of extracellular polysaccharides) is caused by the excessive growth of filamentous bacteria in the sludge mass. This causes deterioration in the mixed liquor settleability characteristics in the secondary settler which can lead to a reduction in the effluent quality due to sludge loss from the system. In two surveys of South African activated sludge plants in 1985 and 1987 by Blackbeard *et al.* (1986, 1988) it was found that about 2/3rds of 110 activated sludge plants (mainly nutrient – N or N & P – removal) and 3/4ths of N & P removal plants (33) experienced sporadic filamentous bulking problems.

When the filaments grow excessively in the sludge they extend from the floc into the bulk liquid and result in either a diffuse floc structure or cause bridging to occur between the flocs. When this happens the sludge flocs are unable to approach each other closely and the sludge does not compact in the settler resulting in a larger sludge volume i.e a bulking sludge. From measurements of the total extended filament length (TEFL) and settleability in terms of the diluted sludge volume index (DSVI), Lee *et al.* (1983) showed that at a TEFL longer than about 30km/g, corresponding to a DSVI greater than 150 ml/g, the filamentous organisms begin to dominate the settling behaviour of the sludge. As a rough guide therefore, a bulking sludge can be accepted as one having a DSVI > 150 ml/g. The sludge volume index (SVI) is not as discriminating as the DSVI in identifying a bulking sludge because the SVI is not as directly related to the TEFL (Lee *et al.*, 1983). However, taking note of reported data, one can accept, roughly, that a SVI between 100 and 200 ml/g is possibly a bulking sludge, and a SVI > 200 ml/g usually is.

Sludge settleability governs the flow and load that can be treated in an activated sludge plant; the operating experience of Northern Works (Johannesburg) clearly demonstrates this (Osborn *et al.*, 1986). For a particular plant in operation the influent peak wet weather flow (PWWF) sets the maximum overflow rate (m/h) in the secondary settling tank, and the daily mass of COD treated (and the sludge age) sets the sludge concentration in the biological reactor. Ekama and Marais (1986a)

showed that a sludge with a DSVI of 150 ml/g can be handled satisfactorily in the settling tank up to a maximum oveflow rate of 1 m/h at a total mixed liquor suspended solids concentration (MLSS) of 3.5 g/l. Should the DSVI deteriorate to 200 ml/g the maximum overflow rate reduces to 0.6 m/h at 3.5 g/l, reducing the treatment capacity of the plant by about 1/3rd. In contrast, if the DSVI is reduced from 150 ml/g to 100 ml/g the overflow rate can be increased to 1.8 m/h increasing the treatment capacity by about 2/3rds.

Thus by preventing bulking and keeping filament proliferation under control (DSVI < 100 ml/g) allows a higher flow and load to be treated in the plant and leads to large savings in operational costs. It also permits smaller settling tanks to be designed for a given sewage flow and load thereby saving money in the initial construction of the plant. These savings that can be made are the driving force behind research into developing specific methods of controlling bulking in long sludge age nutrient removal activated sludge plants in South Africa.

In the surveys mentioned above, the filamentous organisms causing the bulking were identified. It was found that the majority of bulking problems were caused by six filament types. In the first survey of mainly N removal plants the six filaments were, in decreasing order of frequency of dominance, type 0092 dominant in 34% of plants, type 0914 in 24%, *Microthrix parvicella* in 20%, type 1851 in 17%, type 0675 in 16% and type 0041 in 14%. In the second survey of N & P removal plants, the same 6 filaments were the 6 most frequently dominant but in a different order, i.e. 0092 dominant in 82% of plants, 0675 in 45%, 0041 in 39%, *M.parcicella* in 33%, 0914 in 33% and 1851 in 21% (Blackbeard *et al.*, 1986, 1988).

From the surveys it was clear that bulking sludges in long sludge age nutrient removal activated sludge plants in South Africa are dominated by a limited number of filamentous organism types. Of the 6 filaments discussed above 4 types, i.e. 0092, 0041, 0675 and *M.parvicella*, are classified by Jenkins *et al.* (1984) into the low F/M (low food/microorganism ratio) or long sludge age group of filaments. Types 0675 and 0041 are also grouped into the nutrient deficiency group. It was observed that types 0914 and 1851 were frequently found in association with the low F/M filaments and due to this Blackbeard *et al.* (1988) suggested that these 2 filaments also be included in the low F/M filament group. In view of the fact that the low F/M filaments were the principle cause of bulking in South African activated sludge plants

Gabb *et al* (1989a) undertook a 4 year research programme into the development of specific bulking control methods against this group of filaments.

At the time Gabb *et al* (1989a) commenced their research (1985) the accepted method of specific control of low F/M filament bulking was reactor modification which resulted in alternating or sequential feed–starve conditions in the system. This was done by having; (1) intermittent (batch) feeding, (2) multi–reactor or plug flow conditions in the system, or (3) completely mixed systems including selector reactors. In the literature it was hypothesized that these system modifications controlled the bulking by inducing a selector effect in the sludge. The selector effect is the development of a high readily biodegradable COD (RBCOD) utilisation rate by the floc forming organisms in the sludge and is induced under the RBCOD concentration gradient induced by the modifications mentioned. The high RBCOD utilisation rate enables the floc forming organisms to outcompete the filaments for RBCOD substrate in the sludge microenvironment which suppresses filament proliferation and leads to a reduction in the DSVI.

From the work of Gabb *et al.* (1989a), which is reviewed in more detail in chapter 2 of this thesis, it was established *inter alia* that the selector effect was not effective in controlling low F/M filament proliferation in the systems operated. It was observed that continuous aeration was always effective in reducing low F/M filament proliferation: whenever a bulking sludge (DSVI > 200 ml/g) from a full scale N (anoxic–aerobic) or N & P (anaerobic–anoxic–aerobic) removal plant was brought to the laboratory and placed under fully aerobic conditions, low F/M filament proliferation ceased and a DSVI of 50 ml/g was obtained in less than 10 days irrespective of whether or not the systems incorporated the 3 modifications cited in the literature (mentioned above). In contrast it was found that low F/M filament bulking sludges could be developed in laboratory scale nutrient removal systems similar to full scale N and N & P removal plants, i.e. single reactor completely mixed intermittent aeration ditch type N removal plants (Carousel) or multi–reactor anaerobic–anoxic–aerobic N & P removal plants (MUCT/UCT or 3/5 stage Bardenpho). Even when correctly designed selectors were installed ahead of an intermittent aeration (anoxic–aerobic) main reactor, low F/M filaments continued to proliferate and bulking persisted (Gabb *et al.* 1989a). From this research it was concluded that the influent RBCOD, which is removed by floc formers in the selector reactor and in the anaerobic reactor of N & P removal systems, did not appear to

play a major role in low F/M filament bulking as previously thought but that intermittent aeration or the lack thereof (continuous aeration) did.

The finding that the selector effect was unable to control low F/M filament proliferation placed the low F/M filament bulking research back into an exploratory phase. Following this a comprehensive research programme was initiated in 1989 to develop specific methods for controlling low F/M filament bulking in N and N & P removal plants. The main area of interest in the investigation was to establish the influence of

(1) the RBCOD and PBCOD fractions of the sewage
(2) alternating unaerated–aerated conditions
(3) sludge age, and
(4) different plant configurations

on low F/M filament proliferation.

The research reported in this thesis forms part of the comprehensive programme. The investigation centred on three main aspects of item (2) above i.e. the effect of

(1) fully anoxic conditions using both a synthetic sewage and real raw sewage
(2) low nitrate levels in an intermittently aerated single reactor system receiving synthetic sewage feed, and
(3) varying the frequency of alternation between anoxic and aerobic conditions at constant aerobic mass fraction (i.e. increasing the length of the aeration cycle from 72 times per day to once every 3 days while maintaining a constant aerobic mass fraction of 30%) in intermittently aerated single reactor systems fed real sewage

on the low F/M filaments.

In this investigation biological excess P removal, necessitating an anaerobic reactor/phase in N & P removal plants, was avoided and the influence of the above 3 factors was evaluated on laboratory scale continuously fed completely mixed single reactor N removal systems receiving either real or synthetic sewage and operated at 20° C. These conditions were found by Gabb *et al.* (1989a) to consistently promote the proliferation of the problem low F/M filaments identified in the surveys

conducted by Blackbeard *et al.* (1986, 1988).

In chapter 2 a comprehensive literature review is set out so that the objectives of the investigation presented in this thesis can be placed in the context of the current status on specific bulking research for the control of low F/M filaments. In chapter 3 the experimental investigation and results obtained are described in detail. Chapter 4 contains the conclusions formed from the work conducted.

# CHAPTER 2

# SPECIFIC BULKING CONTROL
# REVIEW OF LITERATURE

## PREAMBLE

A comprehensive literature review into specific bulking control is being compiled by Casey *et al.* (1992) as part of the low F/M filament bulking control research programme. That review is presented in this chapter, with a few minor changes, to place the objectives of the investigation outlined in this thesis into context with the current status of specific low F/M filament bulking control research.

## INTRODUCTION

There are two approaches to bulking control, (1) non-specific and (2) specific. With non-specific control some toxicant, usually chlorine although ozone and hydrogen peroxide also can be used, is dosed into the activated sludge system. Because the filamentous organisms causing the bulking extend beyond the flocs into the liquid, they are more exposed to the toxicant and therefore are selectively killed; in contrast the floc formers are not seriously affected by the toxicant because they find protection inside the sludge flocs. Due to the selective killing of the filaments, their numbers are reduced and the bulking is ameliorated. The toxicant affects all filaments irrespective of type and for this reason this method of curing bulking is called non-specific.

The principal non-specific bulking control procedure is by chlorination. This procedure is well documented in the literature such as in the bulking control manual of Jenkins *et al.* (1984). The method has been tested for biological N & P removal systems (Lakay *et al.*, 1988) and found to be satisfactory provided the guidelines set down by Jenkins *et al.* (1984) are followed. However chlorination has a rather serious shortcoming in that undesirable compounds such as trihalomethanes and chlorinated hydrocarbons tend to form which pose a potential health risk. To avoid this problem van Leeuwen (1988) and van Leeuwen and Pretorius (1988) investigated the use of ozone for bulking control in an N & P removal pilot plant. They concluded that ozonation successfully controls filamentous bulking and imparts additional benefits i.e. (1) improves the removal

of organic substances, (2) aids nitrification and to some degree biological excess P removal (BEPR) and (3) produces an effluent that is more suitable for reuse than effluent from activated sludge treatment plants without ozonation.

The problem with non-specific bulking control is that as soon as toxicant dosing is ceased, the filaments regrow and, inexorably, bulking conditions return. This is because non-specific bulking control deals with the symptoms of bulking, i.e. reduces the filaments, but does not remove the causes of the filament proliferation on a permanent basis. With specific bulking control the causes of filament proliferation are sought to be eliminated on a permanent basis.

## SPECIFIC BULKING CONTROL

Specific control of bulking focuses on identifying and eliminating the conditions that promote the proliferation of the specific nuisance filaments causing the bulking problem. Once these conditions are identified, through the types of filaments present in the sludge, it may be possible to create environmental conditions in the activated sludge plant which would inhibit or suppress the growth of the filamentous organisms. If successful, the method would provide a permanent solution to the particular bulking situation.

Five conditions in activated sludge systems have been identified that lead to filamentous organism proliferation (Jenkins *et al.*, 1984), viz. low DO, low Food to Micro-organism ratio (F/M or equivalently long sludge age), nutrient deficiency, septic influent and low pH; each condition favours the growth of certain filamentous organism types (see Table 2.1). From surveys of activated sludge plants in South Africa (Blackbeard *et al.*, 1986, 1988) it was found that the most frequently dominant filamentous organisms in South African activated sludge plants belong to the low F/M group. This is not unexpected because most plants in South Africa are operated at long sludge ages (> 15 days).

In 1973 Chudoba *et al.*(a,b) proposed an organism selection criterion as an explanation for occurrence or non-occurrence of filamentous bulking. This criterion is based on competition between the floc-formers and filaments for mutually limiting soluble substrate, as follows: In the Monod formulation for the specific rate of growth of organisms, filamentous organisms have lower values for both the maximum specific growth rate ($\mu_H$) and the half saturation coefficient ($K_s$) than floc-formers. Consequently at low substrate concentrations the filamentous

organisms have a higher specific growth rate than floc-formers and at high substrate concentrations, a lower specific growth rate (Fig 2.1).

Over the past 15 years the selection criterion has provided a framework for research into the causes of bulking and its control by specific methods. Results, reported by a number of investigators who have measured the Monod constants of various filaments and floc-formers, appear to fit within the structure of the selection criterion: Van den Eynde *et al.* (1982a,b) showed that in general, organisms with high $\mu_H$ rates have high $K_s$ values and ones with low $\mu_H$ rates have low $K_s$ values. Slijkhuis (1983) measured the $\mu_H$ of *Microthrix parvicella* (one of the principal filaments causing low F/M bulking) to be 1,66/d; this is considerably lower than a $\mu_H$ of 4,33/d measured by Richard *et al.* (1982) for a floc-former isolated from activated sludge.

Palm *et al.* (1980) extended the selection criterion to incorporate limiting nutrients: For some filaments (the low DO ones), the limiting nutrient apparently is oxygen whereas for others, the limiting nutrient is the soluble substrate concentration surrounding the organism, as originally conceived by Chudoba *et al.* (1973b). With regard to low DO bulking, Hao *et al.* (1983) and Lau *et al.* (1984) confirmed the work of Palm *et al.* (1980). From dual species studies they showed that low DO filaments (*Sphaerotilus natans*, Type 1701) and floc-formers can be selectively grown by manipulating the DO concentration – if high, the floc-former dominates, if low, the filament dominates.

With regard to bulking in long sludge age (low F/M) systems, Chudoba *et al.* (1973a,b) tested the selection criterion with pure soluble substrates: They controlled the substrate concentration surrounding the organism by having different configurations for the activated sludge system. For example, in a single reactor completely mixed system, the substrate concentration would be low throughout the reactor whereas in a multi reactor plug flow system the substrate concentration would be high in the upstream section and low in the downstream section. They found that in aerobic single reactor completely mixed systems filamentous organisms proliferated causing bulking whereas in aerobic multi-reactor plug flow systems filamentous organisms did not proliferate and a good settling sludge was maintained. From this work, Chudoba *et al.* (1973b) developed the selector reactor for bulking control. The selector reactor is a small aerated reactor upstream of the main aeration reactor and receives the influent

Table 2.1: Dominant filament types as indicators of conditions causing activated sludge bulking

| Suggested causative conditions | Indicative filament types |
|---|---|
| Low DO | type 1701, *S.natans*, *H.hydrossis* |
| Low F/M | *M.parvicella*, *H.hydrossis*, *Nocardia* sp., types 021N, 0041, 0675, 0092, 0581, 0961, 0803 |
| Septic Wastewater/Sulfide | *Thiothrix* sp., *Beggiatoa* and type 021N |
| Nutrient Deficiency | *Thiothrix* sp., *S.natans*, type 021N, and possibly *H.hydrossis* and types 0041 and 0675 |
| Low pH | fungi |

Richard *et al.*, 1982; Strom and Jenkins, 1984.

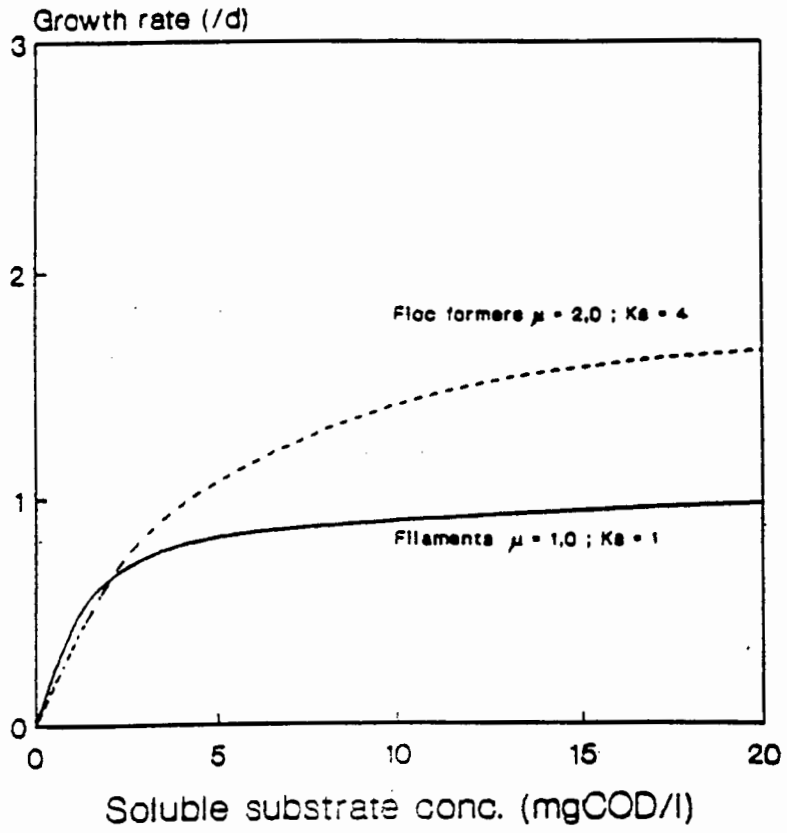



Fig 2.1 Monod specific growth rate functions for filaments and floc forming organisms illustrating the selection criterion of Chudoba *et al.* (1973a,b).

and underflow recycle. In the selector reactor, the substrate concentration is high and, in terms of the selection criterion, the floc-formers should grow faster than the filaments and, will usually utilize practically all of the soluble substrate. The mass of soluble substrate that passes through the selector is a very small fraction of that available to the floc-formers in the selector and so filament growth will be restricted and insufficient to cause bulking.

Although the filament categorization into 5 causative groups was not yet developed – this only emerged in 1984 with the work of Jenkins *et al.* – it should be noted that even though the systems operated by Chudoba *et al.* (1973a,b) were long sludge age or low F/M ones, the filaments causing the bulking were *not* low F/M filaments but were principally one of the low DO filaments, i.e. *S.natans*.
The work of Chudoba *et al.* (1973a,b) stimulated research into the control of bulking in low F/M (long sludge age) systems. Most of this research was conducted on fully aerobic systems at laboratory scale with real or synthetic sewage as influent. In this research it was found that good settling (non-bulking) sludges were produced in systems with:

(1) compartmentalization of the aeration reactor while maintaining continuous feeding of waste water (Chudoba *et al.*, 1974; Rensink *et al.*, 1982; Wu *et al.*, 1984);

(2) batch or intermittent feeding to completely mixed aeration basins (Houtmeyers, 1978; Houtmeyers *et al.*, 1980; Verachtert *et al.*, 1980; van den Eynde *et al.*, 1982a,b; Eikelboom, 1982; Rensink *et al.*, 1982; Goronszy, 1979; Goronszy and Barnes, 1979; Barnes and Goronszy, 1980; Chiesa and Irvine, 1985; Jenkins *et al.*, 1983; Ekama and Marais, 1986b; Still *et al.*, 1986; van Niekerk *et al.*, 1987);

(3) small aerated mixing reactors (aerobic selectors) ahead of the main completely mixed aeration reactor, receiving the influent and underflow streams (Grau *et al.*, 1982; Lee *et al.*, 1982; Jenkins *et al.*, 1983; Daigger *et al.*, 1985; Still *et al.*, 1986; van Niekerk *et al.*, 1987).

As in the investigation of Chudoba *et al.* (1973a,b), in a large number of the investigations cited above, bulking in long sludge age (low F/M) systems was not caused by low F/M filaments. In most cases bulking was caused by *S.natans*

which is a low DO filament. This raised the question of the appropriateness of the system modification approach for controlling low F/M filaments. It appears that in the bulking research, controlling bulking in low F/M systems became the focus rather than controlling bulking by low F/M filaments. These are two distinctly different objectives because bulking in a low F/M system is not necessarily caused by low F/M filaments. As a result of this difference, a point must be made to clearly distinguish between the two terms in the remainder of this review; *low F/M bulking* is bulking in a low F/M system with the filaments causing the bulking unspecified, i.e. could be *S.natans*, whereas *low F/M filament bulking* is bulking caused specifically by the low F/M filaments but this condition need not necessarily be in a low F/M system.

A common characteristic of the three types of systems outlined above is that a soluble COD (<0,45$\mu$m) concentration gradient is induced either in time (i.e. in batch or intermittently fed systems, type 2), or in space (i.e. in compartmentalized or selector reactor systems, types 1 and 2). Some of the investigators concluded that Chudoba's selection criterion does not completely account for the suppression of filamentous organism proliferation and that other factors also play an important role. For example:

(1) Many investigators (Houtmeyers, 1978; Houtmeyers *et al.*, 1980; Verachtert *et al.*, 1980; van den Eynde *et al.*, 1982a,b; Eikelboom, 1982; Jenkins *et al.*, 1983; Daigger *et al.*, 1985; Ekama and Marais, 1986b; Still *et al.*, 1986; van Niekerk *et al.*, 1987), using real or synthetic sewages, provided experimental evidence that systems incorporating the 3 modifications cited above stimulate in the sludge soluble biodegradable COD, i.e. readily biodegradable COD (RBCOD), and oxygen uptake rates that were much higher than in sludge grown in single reactor completely mixed systems with a constant flow and load. They speculated that the soluble COD (RBCOD) concentration gradient induced by the 3 modifications stimulated the growth of floc-forming organisms with high substrate uptake rates. This did not appear to occur in the growth of the filamentous organisms with the result that the filamentous organisms were unable to compete successfully for substrate under these conditions.

(2) Chiesa and Irvine (1982,1985) proposed that the alternating feed–starve conditions induced by the three modifications stimulated development of

floc-formers with a higher starvation resistance than filamentous organisms.

The significance of these factors in bulking control in low F/M (long sludge age) systems is not yet clear but in any event is not really of much consequence. From a practical point of view, provided the system modification controls the bulking problem, it can be implemented for this purpose; detailed explanation and mechanism will follow hand in hand with practical experience. The urgency is in controlling the bulking problems in many activated sludge plants, in particular the low F/M filament bulking problems so common in biological N and N & P removal plants, not only in South Africa but also in other countries.

The system modification approach for bulking control in low F/M systems was also applied by incorporating initial *anoxic* selectors into N removal activated sludge systems. The need for this arose out of the desirability of denitrification for N removal. If an aerobic selector receiving the influent and underflow recycle streams is placed ahead of a nitrification-denitrification system, most of the influent RBCOD will be utilized in the aerobic selector; this will result in a significant loss in denitrification – as much as 50% – in that the influent RBCOD will be utilized with oxygen rather than with nitrate in the primary anoxic reactor. If the selector should be anoxic, the RBCOD will be utilized with nitrate and no loss in denitrification will occur, and if the anoxic selector functions as such, then the conditions for good N removal and selector bulking control are simultaneously met. In laboratory, pilot and full scale work, Heide and Pasveer (1974); Bailey and Thomas (1975); Cooper *et al.* (1977); Tomlinson and Chambers (1979); Wagner (1982); Price (1982); Cooper and Boon (1983) and Shao (1986) reported that in nitrifying activated sludge systems incorporation of initial anoxic mixing zones/selectors ahead of the main aeration reactor improved sludge settleability. However in these investigations, the filaments were either not specified, or where specified were not low F/M types. In evaluating anoxic selectors for bulking control in laboratory scale low F/M systems receiving real sewage, Lee *et al.* (1982), reported that incorporation of two anoxic selectors in series, each 1/74th of the total system volume, did *not* control bulking. Lee and his co–workers sized the selectors in accordance with the volume that would be required to control bulking in aerobic selectors. Based on measurements of soluble COD through the system, they found that not all the soluble biodegradable COD (RBCOD) was taken up in the selectors. The leakage of soluble biodegradable

COD (RBCOD) into the aerobic zone was thought to be the cause for the ineffectiveness of the anoxic selectors. In follow-up laboratory research, Shao (1986) concluded that (1) anoxic selectors controlled bulking in low F/M systems provided that they removed practically all the RBCOD, (2) RBCOD and nitrate uptake rates were significantly higher in the systems incorporating anoxic selectors than systems without anoxic selectors, and (3) uptake rate of RBCOD is slower under anoxic conditions than under aerobic conditions so that anoxic selectors should be sized larger than aerobic selectors.

From the research reviewed above, it would appear that anoxic selectors are effective also for controlling bulking in low F/M systems, but it needs to be pointed out that the filaments present in the laboratory systems operated by Lee *et al.* (1982) and Shao (1986) were not low F/M filaments but 021N, *Thiothrix* and *S.natans.* Consequently it was still not clear whether or not aerobic or anoxic selectors would control the low F/M filaments. In work on denitrification Bailey and Thomas (1975) and Arkley and Marais (1981) found that as the hydraulic retention time of an initial (primary) completely mixed anoxic reactor increased, so sludge settleability in long sludge age systems (20 days) *deteriorated.* In Arkley and Marais' work the anoxic zone had sizes zero (completely aerobic), 39, 50 and 70% of the total system volume. These large anoxic zones cannot be considered selectors in that even though they probably did remove virtually all the RBCOD they almost definitely would not have stimulated a rapid RBCOD uptake rate. Instead of a single large completely mixed primary anoxic reactor Cooper and Boon (1983) installed a channel type anoxic zone by replacing the surface aerators with stirrers in 25% of the aeration basin (normal anoxic hydraulic retention time 2,5h) and a good settling sludge (SVI $< 100$ m$\ell$/g) was maintained. In this work on denitrification, the filamentous organisms were not identified so it is difficult to come to any firm conclusions regarding the effect of the different anoxic conditions on the low F/M filaments.

From the evidence presented in this review so far, it appears that a conclusion widely held was that the selector effect, i.e. the stimulation of a rapid RBCOD uptake rate in an aerobic or anoxic selector, through system modification which introduces a RBCOD concentration gradient in the system, stimulated the growth (or adaptation) of floc formers with high RBCOD uptake rates thus enabling them to successfully compete against the filaments for substrate. While this may be the mechanism of control over certain filamentous organisms, and from the literature

it appears that *S.natans*, *Thiothrix* and 021N are controlled by this mechanism, there was no conclusive evidence that the low F/M filaments were controlled by this mechanism. Because this mechanism had gained considerable credibility as a means of controlling bulking in low F/M systems, its influence on sludge settleability and the low F/M filaments so common in long sludge age biological N and N & P removal systems was thoroughly investigated at laboratory scale by Gabb *et al.* (1989a).

**UNIVERSITY OF CAPE TOWN INVESTIGATION – PHASE 1**

In this investigation (Gabb *et al.*, 1989a), which extended over a period of 4 years, many types of laboratory scale activated sludge systems were operated. As a starting point (phase 1), the type of experiments reported in the literature were repeated to see if the same results could be obtained. This would serve as a useful reference. The types of systems operated were

- fully aerobic constant feed single reactor completely mixed (O/CFCM) and intermittently fed fill and draw (O/IFFO) systems

- fully aerobic constant feed completely mixed systems with aerobic selector (O/CFCM/SEL) and without aerobic selector (O/CFCM).

The need for denitrification required the stimulation of the selector effect in anoxic selectors to be investigated. This was done by operating and evaluating

- anoxic-aerobic constant feed single reactor completely mixed (AO/CFCM) and intermittently fed fill and draw (AO/IFFD) systems that are similar to the fully aerobic O/CFCM and O/IFFD systems cited above except that alternating aerobic/non aeration periods were imposed on the systems.

The sludge age of all these systems was long (20 d), they were fed Mitchell's Plain raw sewage and started up with low F/M filament bulking sludges (DSVI > 250 m$\ell$/g) containing *M.parvicella*, 0675, 0041, 0092 and *Nocardia*.

Conclusions drawn from these first phase experiments were

1. **Stimulation of selector effect**

   The alternating feed-starve conditions imposed by (i) intermittent feeding to

completely mixed reactor systems, either fully aerobic (O/IFFD) or anoxic-aerobic (AO/IFFD) and by (ii) aerobic selector reactors incorporated in fully aerobic continuously fed completely mixed systems (O/CFCM/SEL) stimulated in the mixed liquor a selector effect, i.e. a high readily biodegradable (or dissolved < 0,45$\mu$m filtered) COD (RBCOD) uptake rate. The RBCOD uptake rates were 2 to 3 times higher than in systems that did not incorporate alternating feed-starve conditions (O/CFCM and AO/CFCM). If conditions during which the RBCOD was taken up were aerobic, the high RBCOD uptake rate gave rise to an associated high initial oxygen utilization rate (OUR) under batch conditions and if the conditions were anoxic, an associated high initial nitrate uptake rate under batch conditions was observed.

The selector effect could be stimulated or lost in a sludge over a period less than a sludge age in long sludge age (> 20 d) systems by introducing or eliminating alternating feed-starve conditions. Acquisition of a selector effect by a sludge under alternating feed-starve conditions imposed by the IFFD and CFCM/SEL systems was in agreement with reported results in the literature.

2. **Purely aerobic conditions appear to ameliorate bulking by low F/M filaments**
Low F/M filament bulking sludges (DSVI > 250 m$\ell$/g) usually containing, in varying proportions, types 0092, 0041, 0914, 0675, 1851 and *M.parvicella*, from long sludge age full scale (N removal) plants, when used to start up the laboratory scale long sludge age (> 15 d) activated sludge systems under fully aerobic conditions and the particular anoxic-aerobic conditions, i.e. 1h anoxic 3h aerobic, invariably ceased bulking (DSVI < 80 m$\ell$/g) within a month. This occurred irrespective of whether or not the system incorporated an aerobic selector or the system was intermittently fed or continuously fed, i.e. irrespective of whether the selector effect was stimulated in the system or not. Evidently, in long sludge age fully aerobic systems, and in the particular alternating anoxic-aerobic systems, the selector effect was irrelevant as far as low F/M filament bulking was concerned because the low F/M filament proliferation was suppressed both when the selector effect was present or absent.

3. **Bulking caused by *Sphaerotilus natans* (*S.natans*)**
When bulking was observed in fully aerobic systems and in the particular alternating anoxic-aerobic long sludge systems in which there was no selector

effect (i.e. O/CFCM and AO/CFCM) , it was *not* due to low F/M filaments but due to *S.natans* and *Thiothrix*. According to Jenkins *et al.* (1984) *S.natans* sorts into the low DO group and *Thiothrix* into the septic sewage or nutrient deficient groups. However in the surveys of South African full scale N and N & P removal plants *S.natans* had not, and *Thiothrix* had only rarely, been observed to cause bulking in these long sludge age plants.

4. ***S.natans* bulking apparently caused by seeding**
   Regular and thorough cleaning of the influent feed lines eliminated the *S.natans* bulking problems in the laboratory systems. From this it was concluded that *S.natans* proliferation in the laboratory systems was caused by seeding from *S.natans* attached growth on the influent feed line walls. This artifact may also have been present in the many laboratory scale studies throughout the world cited above because numerous investigators have reported the proliferation of *S.natans* in their low F/M (long sludge age) laboratory systems under a wide range of operating conditions.

5. **Selector effect controls *S.natans* and *Thiothrix***
   Aerobic selectors and intermittent feeding conditions, which induce the selector effect, controlled the proliferation of *S.natans* and *Thiothrix*. This finding is in conformity with results reported in the literature cited above.

Up to this point in the investigation, the results obtained were in conformity with those reported in the literature – in particular, a general absence of low F/M filaments in the systems, and, when bulking did take place, it was caused by *S.natans*, *Thiothrix* and 021N and occurred only in the systems which did not stimulate a selector effect. However, Gabb *et al.* (1989b) showed that *S.natans* in particular, proliferated in the systems as a result of seeding from the influent feed lines, and that when the feed lines were regularly cleaned (chlorinated twice weekly) *S.natans* no longer proliferated in the systems. In the systems which stimulated a selector effect *S.natans*, *Thiothrix* and 021N did not proliferate indicating that the selector effect, stimulated under either aerobic or anoxic conditions, controlled bulking by *S.natans* and *Thiothrix*. This obsèrvation is in conformity with the results published in the literature. The success of the selector effect in controlling bulking by *S.natans* and *Thiothrix* in laboratory scale low F/M systems appears therefore to have contributed to the notion in the literature that the selector effect also controls low F/M filament bulking.

In the laboratory systems operated by Gabb *et al.* (1989a), the low F/M filaments did not proliferate – indeed from conclusion (2) above the low F/M filament bulking problems in the starter sludge were ameliorated in all the systems operated. However in marked contrast to these findings it was observed that, in biological N & P removal systems [which comprise anaerobic-anoxic-aerobic zones usually in single or multi reactors in series and incorporating an appreciable (50%) unaerated sludge mass fraction] operated in the laboratory at the time of these experiments, the low F/M filaments did proliferate and cause bulking problems. Indeed, of the laboratory systems operated at the time (which were those cited above and the N & P removal ones) the N & P removal systems were the only ones in which the filament populations were similar to their full scale counterparts i.e. low F/M filaments proliferated, *S.natans* was absent and *Thiothrix* filaments were not commonly observed, even when the feed lines were not regularly cleaned.

From the absence of *S.natans* and *Thiothrix* in N & P removal systems, it was hypothesized that the anaerobic reactor in these systems operates as a selector reactor against *S.natans* (and possibly *Thiothrix*) proliferation. This hypothesis finds support from the laboratory experiments of Wanner *et al.* (1987a, 1987b) who calls this type of selection metabolic selection (as opposed to competitive selection in aerobic selectors) which operates as follows: *S.natans* is an obligate aerobe (Mulder and Deinema, 1981) and only capable of metabolism in the fully aerobic reactor. However in the anoxic reactor, the RBCOD is utilized by denitrifiers and in the anaerobic reactor, RBCOD is converted to volatile fatty acids (VFA) which together with the VFA from the influent, is taken up by polyphosphate accumulating organisms such as *Acinetobacter* spp. (Wentzel *et al.*, 1985). Consequently with anaerobic and/or anoxic reactors in the system very little RBCOD enters the aerobic reactor for growth of *S.natans*. In terms of this explanation, selectors, whether aerobic, anoxic or anaerobic, control *S.natans* proliferation either by (i) removing RBCOD under conditions in which *S.natans* cannot function (anaerobic or anoxic selectors i.e. metabolic selection) or (ii) stimulating high RBCOD uptake in floc-formers which then can compete successfully against *S.natans* (aerobic selectors i.e. kinetic selection). With regard to *Thiothrix*, this organism is reported to be a facultative anaerobe. If it is a facultative organism, anaerobic reactors, anoxic and aerobic selectors should control its proliferation. The literature supports this conclusion in that *Thiothrix* is controlled by anaerobic reactors (Wanner *et al.*, 1987b), anoxic selectors (Shao, 1986) and aerobic selectors (van Niekerk, 1985).

From the above discussion it can be seen that with respect to the filaments *S.natans*, *Thiothrix* and 021N there is consistency of behaviour in the anaerobic reactor as metabolic selector and aerobic and anoxic selectors as competitive selectors in that in all three RBCOD is taken up preferentially by floc formers at the expense of the filaments. The observation that the anaerobic reactor in its function as a metabolic selector, does *not* control the proliferation of low F/M filaments in N and N & P removal systems because these types of plants so frequently have low F/M filament bulking, raises the question whether or not aerobic and anoxic selectors will be able to control low F/M filament proliferation through competitive selection. Aerobic and anoxic selectors and anaerobic reactors permit removal of influent RBCOD by floc-formers through competitive or metabolic selection, but despite this the low F/M filaments continue to proliferate in N & P removal systems. Therefore it would appear that the low F/M filaments do not require RBCOD for growth to the same extent as *S.natans*, *Thiothrix* and 021N do. If the low F/M filaments are able to grow on COD other than RBCOD, i.e. the particulate biodegradable COD (PBCOD), then because the PBCOD passes through the aerobic/anoxic selectors and anaerobic reactors, the proliferation of these filaments would not be controlled by aerobic and anoxic selectors. Based on this reasoning the second phase of the investigation by Gabb *et al.* (1989a) focused on ascertaining whether or not aerobic selectors could suppress low F/M filament proliferation.

Before the efficacy of aerobic (or anoxic) selectors in suppressing low F/M filament proliferation through competitive selection could be determined, it was necessary to devise a laboratory system other than an N & P removal one, wherein low F/M filaments proliferated. To do this attention was focused on unaerated/aerated systems, because it was evident from the first phase of the investigation and from the bulking surveys that low F/M filaments proliferate in full scale unaerated/aerated systems, irrespective of whether these were biological N & P removal systems or N removal only systems. Accordingly in this second phase of the investigation various kinds of unaerated/aerated systems were operated.

Initially three single reactor systems were started up with a low F/M filament bulking sludge harvested from a laboratory scale N & P removal (Modified UCT) system. All three systems were operated at the same sludge age (20 d) and received the same sewage as the parent MUCT system. Two of the systems were

intermittently fed once daily while the third was continuously fed. One of the intermittently fed systems was anaerobic for the first 6h after feeding, aerobic for 16 h, then finally settling for 2 h. The other intermittently fed system, and the continuously fed system, were maintained fully aerobic for 24 h. In the two fully aerobic systems, the DSVI declined steadily from a start-up value of around 200 m$\ell$/g to below 60 m$\ell$/g over a period of 2 to 3 sludge ages. Over the same period, the DSVI in the intermittently fed anaerobic-aerobic system and in the parent MUCT system remained high between 180 and 200 m$\ell$/g.

These experiments demonstrated that (1) continuous aeration inhibits the growth of most of the low F/M filaments, in particular *M.parvicella*, 0092 and 0914 irrespective of whether or not alternating feed starve conditions prevail (intermittently or continuously fed), and (2) an initial anoxic-anaerobic period of 6 h during which all the RBCOD is removed from the liquid phase, followed by an aerobic period of 16h, at a DO of 6 mgO/$\ell$ and the anaerobic (9,6h), anoxic (11,2h), aerobic (14,4h) sequence of the parent MUCT system, allows low F/M filaments to proliferate and cause bulking. However, it was not clear how the continuation of bulking by low F/M filaments in the intermittently fed anaerobic/aerobic system fitted in with the amelioration of low F/M filament bulking observed in the anoxic-aerobic (AO/IFFD) and continuously fed (AO/CFCM) systems operated in phase 1 of the investigation (see 2 above). Nevertheless it was concluded from these experiments, and from the survey of filamentous organisms in full scale plants, that low F/M filaments proliferate in plants that have alternating aeration-non aeration either in different reactors or in different temporal stages of the same reactor.

In an attempt to grow low F/M filaments in laboratory systems other than N & P removal ones, long sludge age single reactor continuously fed completely mixed systems with intermittent aeration (1 minute air on, in a 10 minute cycle with peak DO of 2,0 mgO/$\ell$) and fed real sewage were set up to mimic Carousel or Orbal type N removal plants. It was found that in such systems most of the low F/M filaments proliferated, in particular *M.parvicella* and 0092 but also 0914, 0041, 0675 and 1851. Switching these systems from intermittent to continuous aeration invariably caused a sharp decline in DSVI with a concomitant reduction in low F/M filaments and amelioration of the bulking. Switching back to intermittent aeration caused regrowth of the low F/M filaments and associated bulking, confirming that the low F/M filaments respond very strongly to the

presence or absence of unaerated periods in the system.

Having established that low F/M filaments proliferated in laboratory scale intermittent aeration systems it then became possible to check whether or not aerobic selectors control low F/M filaments. This was done by setting up an experimental and a control system. Both were single reactor, continuously fed completely mixed intermittently aerated systems. With a correctly sized multi-compartment aerobic selector installed on the experimental system, it was found that the selector effect *did not* control most of the low F/M filaments. The DSVI remained above 250 m$\ell$/g in both systems for more than 5 sludge ages (100 days). The presence of the selector effect in the experimental system sludge was verified by doing (i) batch tests to check that rapid RBCOD and oxygen uptake rates had been stimulated, (ii) soluble COD profiles in the selector reactors to see that all the RBCOD was taken up in the selectors and (iii) microscopic examination which confirmed that numerous Zoogleal colonies had formed. Switching the control system to continuous aeration caused the DSVI to decrease sharply in 10 days, with a concomitant decline in low F/M filaments, while the DSVI in the experimental system with the selector reactors remained high.

## CONCLUSIONS FROM THE INVESTIGATION

1. The observation that aerobic selectors did not control bulking by low F/M filaments, in particular types 0092, 0041, 0675 and *M.parvicella*, resolved the inconsistency with respect to the low F/M filaments in the behaviour between metabolic selection in anaerobic reactors (in N & P removal plants) and kinetic selection in aerobic selectors. In N & P removal plants anaerobic reactors which stimulated preferential removal of influent RBCOD by floc-formers (Wentzel *et al.*, 1985) did not control low F/M filament proliferation. Aerobic (and by implication presumably also anoxic) selectors which promoted preferential removal of influent RBCOD by stimulating the selector effect also did not control low F/M filament proliferation. From this it would appear that the influent *RBCOD* does not play an important role in the growth of low F/M filaments in long sludge age systems. It would seem then that the possibility exists that the low F/M filaments utilize particulate biodegradable COD (or its hydrolysis products) originating either from the influent or self-generated within the system by death and lysis of organisms (Ekama and Marais, 1986b).

2. Low F/M filaments appeared to proliferate in systems that exposed the sludge mass to alternating anoxic-aerobic periods as in anaerobic-anoxic-aerobic multi reactor N & P removal systems and completely mixed intermittently aerated N removal systems (ditch type plants). When these systems, or sludge harvested from these systems, was exposed to purely aerobic conditions by continuous aeration, the low F/M filament bulking was ameliorated and sludge settleability improved (DSVI < 80 mℓ/g). From this it would appear that the anaerobic/anoxic conditions that are required to stimulate biological N or N & P removal could also stimulate proliferation of low F/M filaments in long sludge age systems, and unfortunately fully aerobic conditions which inhibit low F/M filament proliferation also inhibit biological N or N & P removal. Consequently to effect specific control over the low F/M filaments, some environmental condition needs to be found that will lead to exclusion of the filaments but retention of the organisms and conditions that effect biological nutrient removal. At the conclusion of the investigation of Gabb *et al* (1989a) such an environmental condition was not known.

3. It was considered most likely that it is the anoxic-aerobic alternation that leads to the low F/M filament proliferation because this is a common feature in N & P removal and completely mixed ditch type N removal systems. No answers were offered as to the effects of the magnitude of the anoxic mass fraction, the length of anoxic retention time (actual or nominal), the duration of the anoxic-aerobic cycles in intermittent aeration systems, the concentration of nitrate during the anoxic periods, the frequency of alternation between anoxic and aerobic periods or the effect of the low DO concentrations which arise during the 'lead-in' to anoxic conditions.

## RECOMMENDATIONS FOR FURTHER RESEARCH

From the investigation and conclusions of Gabb *et al.* (1989a) discussed above a number of questions emerged which served as a useful guide for further research into specific low F/M filament bulking control; viz

1. Which components in the influent wastewater are responsible for the growth of low F/M filaments and hence bulking? Because the influent RBCOD apparently does not play an important role in the sense that the filaments can proliferate without it, can the low F/M filaments utilize the influent particulate biodegradable COD (PBCOD)? It was anticipated that the

influent PBCOD does play a role in the growth of the low F/M filaments because this COD is not significantly reduced in selector reactors (whether aerobic or anoxic and anaerobic reactors) and therefore passes through to the anoxic and aerobic zones of the system. For the purpose of identifying the role of the influent PBCOD and RBCOD, it was proposed to develop and refine an artificial sewage of known composition, which would support the growth of the low F/M filaments. The artificial sewage could be fed to nutrient removal and completely mixed intermittent aeration systems and the filament populations that developed with the artificial sewage would be compared with the filament populations in similar systems fed real sewage. The constituents of the artificial sewage could be manipulated to observe the influence of the RBCOD and PBCOD on the low F/M filaments.

In addition to developing an artificial sewage, real sewage can be readily separated into its RBCOD and PBCOD constituents by modern ultrafiltration techniques. The RBCOD and PBCOD, appropriately reconstituted to its original volume with tap water, could be fed to various laboratory scale N and N & P removal systems to observe the effect of the substrate on the low F/M filaments and system performance.

2. If PBCOD only supports the growth of the low F/M filaments, do the filaments utilize hydrolysis products of the PBCOD in the liquid generated by other organisms or are they able to hydrolyze and utilize PBCOD directly themselves? Are the low F/M filaments able to utilize (either directly or indirectly) the substrate originating from the lysis of dead organisms in the biomass (Ekama and Marais, 1986b)? If influent PBCOD, or its hydrolysis derivatives, can be utilized by the low F/M filaments, what causes the filaments to proliferate under unaerated-aerated conditions but not purely aerated conditions?

3. Due to the strong influence of the periodic unaerated-aerated conditions in biological N and N & P removal plants – most likely the anoxic conditions because this is common to both N and N & P removal plants – investigate the influence of the characteristics of the anoxic reactor on low F/M filament bulking; characteristics like:
   (i) type – in an intermittently aerated system or in a multi-reactor system as a primary anoxic or secondary anoxic zone.

(ii) size – because low F/M filaments proliferate (DSVI > 300 mℓ/g) in unaerated-aerated systems with large unaerated fractions (– 70%) and not (DSVI < 80 mℓ/g) in purely aerated systems (0% unaerated) is there a trend that the greater the unaerated fraction, the higher the DSVI? From Arkley and Marais (1981), this would appear to be the case. Unfortunately in their work the filaments were not identified, but these were probably low F/M filaments because *S.natans*, *Thiothrix* or 021N are rarely found in laboratory multi-reactor anoxic-aerobic (N removal) or anaerobic-anoxic-aerobic (N & P removal) systems in which all the influent is discharged into the anoxic or anaerobic reactors. Can the low F/M filaments proliferate under fully anoxic conditions?

(iii) nitrate – investigate the effect of the nitrate concentration in the anoxic zone on the proliferation of low F/M filaments.

(iv) frequency of alternation between anoxic and aerobic conditions – in the intermittent aeration systems the aeration cycle establishes the number of times the sludge is switched between anoxic and aerobic conditions, and in multi-reactor anoxic aerobic systems this is established by the recycle ratios; does this frequency of alternation between the anoxic and aerobic conditions have an influence on the low F/M filament proliferation?

4. Because these low F/M filaments supposedly proliferated in long sludge age systems, at what sludge age is their proliferation suppressed so that the sludge settleability is at most a DSVI of 100 mℓ/g? Is N and N & P removal possible at this sludge age?

5. Attempt to control low F/M filament bulking in different system configurations which incorporate biological N or N & P removal. For example:

(1) a system configuration which minimizes utilization of *influent* PBCOD under anoxic conditions (but not that generated by organism death and lysis) is the Johannesburg system, with anaerobic and aerobic zones following sequentially and an anoxic zone in the *underflow* recycle stream for denitrification of the return sludge to the anaerobic reactor. If such a

system inhibits proliferation of low F/M filaments compared to a modified UCT system, it would indicate that the filaments utilize influent PBCOD, or a derivative of influent PBCOD, under anoxic conditions.

(2) the reason why sludge ages in N and N & P removal plants are long (> 20 days) is to ensure nitrification. Wanner *et al.* (1988) investigated the influence of fixed media in the aerobic zone of N or N & P removal plants on the nitrification rate. With this approach it may be possible to maintain a long aerobic sludge age on the fixed media for nitrification while the suspended sludge has a sludge age sufficiently short to suppress low F/M filament proliferation.

**FURTHER RESEARCH**

The above research areas are clearly wide ranging and in order to investigate them a second comprehensive laboratory research investigation was commenced in 1989. The research presented in this thesis forms part of this investigation and, in order to place it in the context of the investigation, a brief review of the progress of the investigation relevant to this thesis is given below

(1) **Development of a synthetic sewage feed supporting low F/M filament growth**

This work was commenced by Gabb *et al* (1989a) (although not reported by them) and followed 3 steps :

(1) Chemical Composition: Nutritional requirements insofar as readily (RBCOD) and particulate (PBCOD) biodegradable COD constituents were concerned were established for most of the activated sludge bacteria from the literature. In addition the principle chemical constituents of the Mitchell's Plain raw sewage and of other domestic sewages reported in the literature were established. The composition of the Mitchell's Plain raw sewage was important because this was the sewage fed to the laboratory scale activated sludge systems which were compared with the systems fed the synthetic sewage. From the chemical analyses a defined substrate (synthetic sewage) was formulated which was progressively refined after experimentation on activated sludge systems in steps (2) and (3) below.

(2) Kinetic response: The correct proportions of RBCOD and PBCOD were determined by comparing the batch test results using the synthetic sewage with those using Mitchell's Plain raw sewage. RBCOD and PBCOD proportions were varied until they matched those of the raw sewage.

(3) Microbiological Response: The ability of the low F/M filaments to proliferate in the systems fed the synthetic sewage was evaluated. For this purpose two experimental laboratory systems were operated receiving the synthetic sewage, both with control systems receiving Mitchell's Plain raw sewage. It was found that an unaerated – aerated (6 hrs unaerated, 16 hrs aeration, 2 hrs settling) intermittently fed fill and draw (IFFD) system receiving synthetic sewage feed promoted the abundant growth of the following filaments; types 0092, 0914, 0041, 0675, 0803, *Haliscomenobacter hydrossis* and *Nostocoida limicola* II. All of these filaments had been observed in bulking sludges of full scale plants (the first four named more common than the last three) in the surveys of Blackbeard *et al.* (1986, 1988). During these experiments the inorganic nutrient concentrations of the synthetic sewage were adjusted to prevent these being growth limiting.

### (2) The work of Casey *et al* (1990) with the synthetic sewage

The synthetic sewage developed by the procedure above was used later in experiments by Casey *et al* (1990) with only the RBCOD and PBCOD proportions being varied. During these experiments in which continuously fed long sludge age single completely mixed reactor intermittent aeration (2 min on, 20 min off) systems were operated, it was found that the fats and oils part of the PBCOD component of the synthetic sewage, thought to be important for the growth of low F/M filaments such as *M.parvicella* (Slijkhuis, 1983) did not cause *M.parvicella* to grow in the systems and had no observable effect on the filament populations which developed in the systems. Consequently Casey *et al* (1990) removed the fats and oils from the synthetic sewage used in the remainder of the investigation. To compensate for the COD 'lost' by the exclusion of the fats and oils the PBCOD concentration of the synthetic sewage was increased. The constituents of the final synthetic sewage fed to the systems operated in the investigation is given in Appendix A.

# CHAPTER 3

# EXPERIMENTAL INVESTIGATIONS

## 3.1 EXPERIMENTAL OVERVIEW

The experimental investigation into the effect of fully anoxic conditions and the frequency of alternation between anoxic and aerobic conditions on low F/M filament bulking was divided into three separate phases studying :

(1) the effect of (a) fully anoxic conditions, and (b) the magnitude of the nitrate concentration during the anoxic period of an intermittent aeration cycle, in long sludge age continuously fed single completely mixed reactor systems receiving synthetic sewage as feed (147 days)

(2) the effect of fully anoxic conditions in long sludge age continuously fed single completely mixed reactor systems receiving real sewage (44 days)

and (3) the effect of the frequency of alternation between anoxic and aerobic conditions from 48 times per day to once every 3 days in long sludge age continuously fed single completely mixed reactor intermittent aeration systems receiving real sewage (241 days)

During all three phases of the experimental investigation the following parameters were measured daily, viz :

1. Influent and effluent (unfiltered) COD concentration.
2. Influent and effluent (unfiltered) TKN concentrations (mgN/l).
3. Effluent nitrate concentration (mgN/l).
4. Reactor MLSS concentration.
5. Reactor MLVSS concentration.
6. Sludge settleability in DSVI (ml/g).
7. Oxygen utilisation rate (OUR), when applicable, in mgO/l converted to mgO/gVSS.
8. Peak DO concentration during the aeration cycle (when applicable).
9. Aerobic fraction i.e. the fraction of the total time that the sludge mass was aerated (when applicable).
10. Filament identification (done every 3–4 weeks).

During the investigation a number of changes were made to the experimental systems and occasionally operational problems were encountered. These operational

changes made and problems encountered that affected the operation of the system, and therefore possibly the results, are presented in tabular form for each phase. Also the daily measured results are presented graphically for each phase and discussed together with operational changes and problems in the relevant sections below.

## 3.2 PHASE 1 THE EFFECT OF FULLY ANOXIC CONDITIONS AND THE NITRATE CONCENTRATION DURING THE ANOXIC PERIOD ON LOW F/M FILAMENT BULKING IN CONTINUOUSLY FED SINGLE COMPLETELY MIXED REACTOR SYSTEMS.

Because the proliferation of low F/M filaments had been demonstrated in long sludge age continuously fed single completely mixed reactor systems with intermittent aeration and fed synthetic or real sewage feeds (Gabb *et al*, 1989a, Casey *et al*, 1990 and Warburton *et al*, 1991) with a weak but positive influence of the nitrate concentration during the anoxic period on the proliferation of the low F/M filaments (Warburton *et al*, 1991), continuously fed single completely mixed reactor systems were selected for this investigation to test the effect of fully anoxic conditions and to verify the effect of low nitrate concentrations during the anoxic period of an intermittent aeration cycle on the low F/M filaments.

### 3.2.1 Experimental Set–up

Two laboratory scale single reactor completely mixed continuously fed systems were started up, one control (CFR 1) and one experimental (ANOX 1). Both systems were fed the synthetic sewage previously shown to stimulate the growth of low F/M filaments in similar intermittently aerated systems (see chapter 2, details of constituents of synthetic sewage are given in Appendix A). System CFR 1 served as a control intermittently aerated system against which to compare the results of the fully anoxic system ANOX 1. In addition CFR 1 served as an experimental system to check if the previously observed effects of low nitrate levels during the anoxic period of intermittent aeration (i.e. a decrease in DSVI) with real sewage feed were reproducible with synthetic sewage.

The initial operating conditions of CFR 1 were set up to be the same as those previously found to stimulate low F/M filament proliferation with synthetic and real sewage feeds, viz (1) long sludge age (15 days), (2) short intermittent aeration cycle i.e. 15 minute aeration cycle with 1 minute aeration to give a peak DO of

2–2.5 mgO/l, (3) small aerobic mass fraction (30%) and (4) nitrate addition (Gabb *et al*, 1989a, Warburton *et al*, 1991). Details of the initial operating conditions for the systems CFR 1 and ANOX 1 are given in Table 3.1. The two systems CFR 1 and ANOX 1 were taken over from an earlier experiment during which both were intermittently aerated receiving synthetic sewage feed and had nitrate supplemented to them to ensure sufficient nitrate for denitrification during the anoxic period resulting in an effluent nitrate concentration of about 20mgN/l. System CFR1 had been fed a synthetic sewage with a high RBCOD content, whereas ANOX 1 had been fed a synthetic sewage with RBCOD and PBCOD constituents in proportion to real sewage. Soon after commencement of this investigation the nitrate supplementation to CFR 1 was stopped and the only nitrate in the system was that produced by nitrification during the aerobic period of the aeration cycle. Nitrate supplementation was stopped to observe the effect of low nitrate levels during the anoxic period on the growth of low F/M filaments. Details of all the changes, both by design or accident, made to systems CFR 1 and ANOX 1 during phase 1 of the experimental investigation are listed in Tables 3.2 and 3.3 respectively.

### 3.2.2 Results and Discussion

The experimental results measured daily on systems CFR 1 and ANOX 1 are given graphically in Fig 3.1 to 3.9 as follows ;

- Fig 3.1 Influent and effluent COD (unfiltered)
- Fig 3.2 Influent and effluent TKN (unfiltered)
- Fig 3.3 Influent (when dosed) and effluent $NO_3$ (filtered)
- Fig 3.4 Reactor MLSS and MLVSS
- Fig 3.5 OUR for CFR 1 during aerobic period
- Fig 3.6 Peak DO for CFR 1
- Fig 3.7 Aerobic mass fraction for CFR 1
- Fig 3.8 DSVI and filament identification for CFR 1
- Fig 3.9 DSVI and filament identification for ANOX 1

**System behaviour — COD Balance**

As can be seen in Figs 3.1 to 3.9 the experimental data obtained during the operation of systems CFR 1 and ANOX 1 showed a relatively high degree of variability. Due to this a COD balance needed to be calculated using the data to ascertain its reliability. To perform a COD balance the measured total influent mass of COD, $M(S_{ti})$, is compared with the total mass of COD leaving the system. The

**Table 3.1** : **Initial operating conditions and parameters for the systems, CFR 1 and ANOX 1, operated during phase 1 of the investigation. Both systems received a synthetic sewage as feed.**

| System | ANOX 1 | CFR 1 |
|---|---|---|
| Operating Conditions | Continuously Fed Completely Mixed Single Reactor | |
| Aeration | None | Intermittent |
| Aerobic Mass Fraction | | 25–40 % |
| Aeration Cycle | | 15–30 minutes |
| DO Concentration (mgO/l) | | 0–2.5 |
| Sewage Source | Synthetic Sewage | |
| Mass of COD fed/d | 5000 – 6000 | 5000 – 6000 |
| Volume of feed (l/d) | 10 | 10 |
| Concentration (mgCOD/l) | 500–600 | 500–600 |
| Influent TKN (mgN/l) | 45–70 | 45–70 |
| Sludge Age (days) | 15 | 15 |
| Temp. (Deg C) | 20 | 20 |
| Reactor Volume (l) | 7.5 | 7.5 |
| pH of Mixed Liquor | 7.4–7.8 | 7.4–7.8 |
| Recycle Ratio | 1:1 | 1:1 |
| MLSS Conc. (mg/l) | 1500–2800 | 1100–3000 |
| VSS Conc. (mg/l) | 1400–2500 | 1000–2700 |

Table 3.2 : Operational changes and problems for CFR 1 during phase 1; system intermittently aerated and receiving synthetic sewage.

| Day | Change | Reason or Problem |
|---|---|---|
| 0 | Startup system | |
| 6 | $NO_3$ feed discontinued but aeration continued | To observe effect of lower $NO_3$ with average synthetic sewage (30% aerobic) |
| 7 | Aeration cycle set @ 15 min. | To maintain 30% aerobic |
| 11 | Aeration cycle set @ 20 min. | OUR decreased (30% aerobic) |
| 12 | Aeration cycle set @ 17 min. | To maintain 30% aerobic |
| 14–36 | | Overflow tube blocked fairly often and sometimes overflowed with sludge loss. |
| 37 | Extra overflow tube fitted | To prevent system overflow and sludge loss |
| 46 | Overflow tube continually knocked with mechanical arm | To prevent clogging |
| 53 | | Aeration tube disconnected and system not aerated for ± 16 hrs. System anaerobic and effluent cloudy. |
| 56 | Aeration cycle set @ 30 min. | Low OUR (30% aerobic) |
| 67 | Sludge sieved and reactor brushed to resuspend solids | Sludge settling in reactor and clogged in overflow tube and settler. Large clumps forming Contents of reactor almost clear. |
| 74 | | Sludge very dark in colour & effluent very cloudy. System appears anaerobic during the 'anoxic' period. |
| 75 | Aeration cycle set @ 20 min. | Maintain 30% aerobic |
| 77 | Start $NO_3$ feed to system | To ensure anoxic conditions during the non–aerated period |
| 80–118 | | Sludge accumulating in settler and needed to be replaced in system regularly |
| 89 | | Feed pump off and no feed for ±14 hrs |
| 101 | | Feed tube split and no feed |

Table 3.2 : continued

| | | |
|---|---|---|
| 104 | System seeded with 1300ml of bulking sludge (DSVI ±150ml/g) Aeration cycle set @ 25 min. | To increase DSVI and prevent sludge accumulation in the settler maintain 30% aerobic |
| 108 | System seeded with 2l of bulking sludge (DSVI ±150ml/g) | Same as 104 |
| 114 & 5 | System seeded with 500ml of bulking sludge per day | Same as 108 |
| 118 | System closed down | Sludge continually accumulating in settler and showing no signs of recovery. |

Table 3.3 : Operational changes and problems for ANOX 1 during phase 1 ; fully anoxic system receiving synthetic sewage

| Day | Change | Reason or Problem |
|---|---|---|
| 0 | Startup ANOX 1 | |
| 6 | Aeration switched off. Start $NO_3$ feed. System sealed. | To ensure fully anoxic conditions (as far as possible) |
| 29 | Renew $NO_3$ feed tube | $NO_3$ feed tube split |
| 54 | Renew $NO_3$ feed tube | $NO_3$ feed tube split overnight and no feed for several hours |
| 56 | Reduce $NO_3$ feed concentration | To observe the effect of low $NO_3$ levels |
| 57 | | Effluent cloudy |
| 58 | | System anaerobic overnight due to blocked $NO_3$ feed tube |
| 62 | | Settler failure & sludge lost replaced in system |
| 67 | | Dark grey sludge indicating anaerobic conditions due to too low $NO_3$ feed. |
| 68 | | Settler failure, sludge replaced in system |
| 69 | $NO_3$ feed concentration incr. | To prevent anaerobiosis.<br>Settler failure, sludge replaced in system |
| 71 | $NO_3$ feed conc. increased | |
| 72–74 | | Settler failure, sludge replaced in system<br>Sludge light brown in colour indicating anoxic conditions |
| 80 | Renew $NO_3$ feed tube | $NO_3$ feed tube blocked |
| 89 | | Pump failure, no sewage feed for 14 hrs |
| 101–3 | | Low $NO_3$ feed, system anaerobic, settler failure on day 103 |
| 119 | $N_2$ bubbled through system & overflow tube | To ensure complete anoxic conditions<br>pH incr. to 8.83 |

Table 3.3 : continued

| | | |
|---|---|---|
| 120 | | Lot of sludge in effluent bucket, replaced in system |
| 121 | | Pump failure overnight and system fed continuously. System not fed for several hours. |
| 138 | | Pump failure as on day 121 |
| 147 | System closed down | Wrong filaments growing in system. |

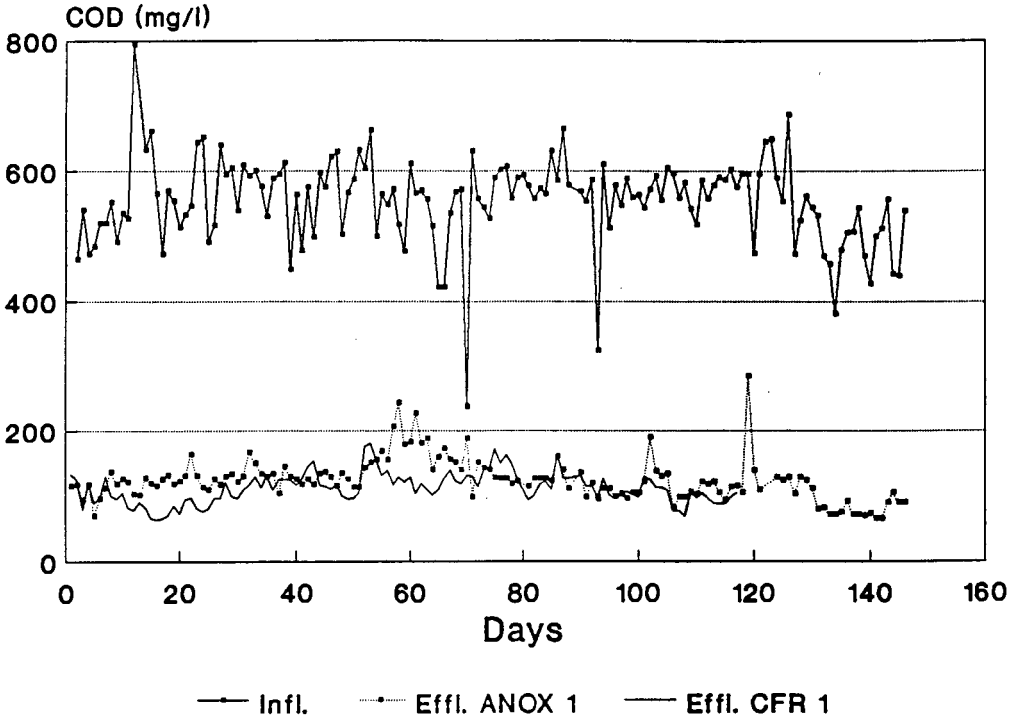



Fig 3.1 : Influent and effluent (unfiltered) COD concentration measured daily for CFR 1 and ANOX 1 during phase 1 of the investigation with both systems receiving synthetic sewage with RBCOD and PBCOD fractions in proportion to real sewage (25% RBCOD and 75% PBCOD).

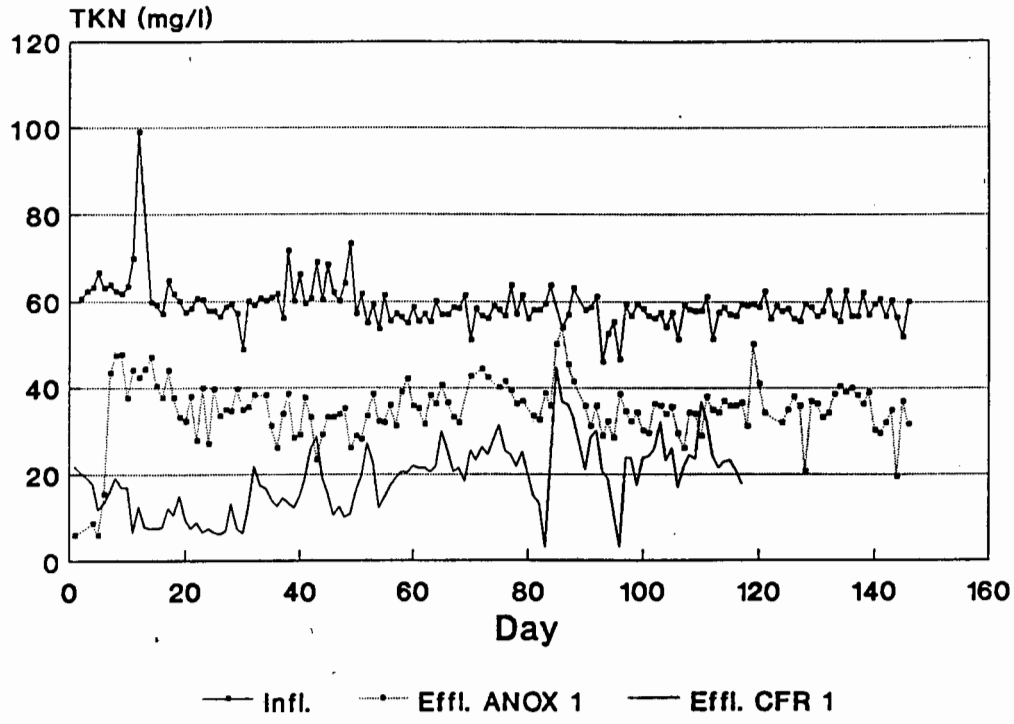
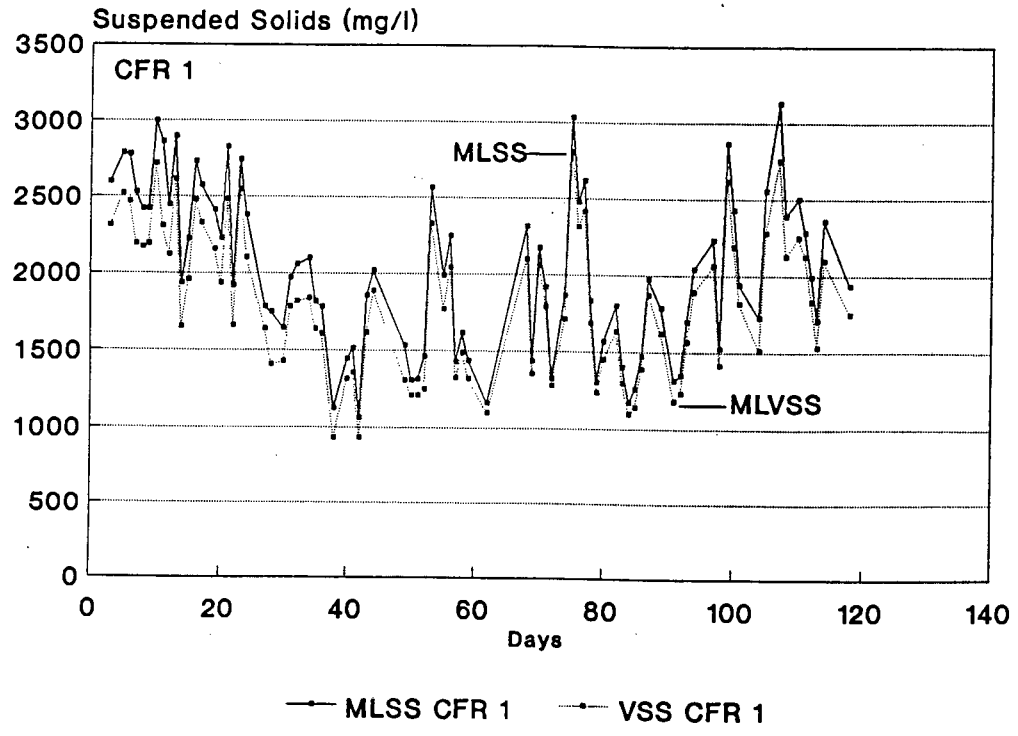



Fig 3.2 : Influent and effluent TKN concentration (unfiltered) measured daily for CFR 1 and ANOX 1 during phase 1 of the investigation with both systems receiving synthetic sewage with RBCOD and PBCOD frations in proportion to real sewage (25% RBCOD and 75% PBCOD). Note the increase in the effluent TKN for CFR 1 over the experimental period due to nitrification no longer being complete (see Fig 3.5).

(a)




(b)

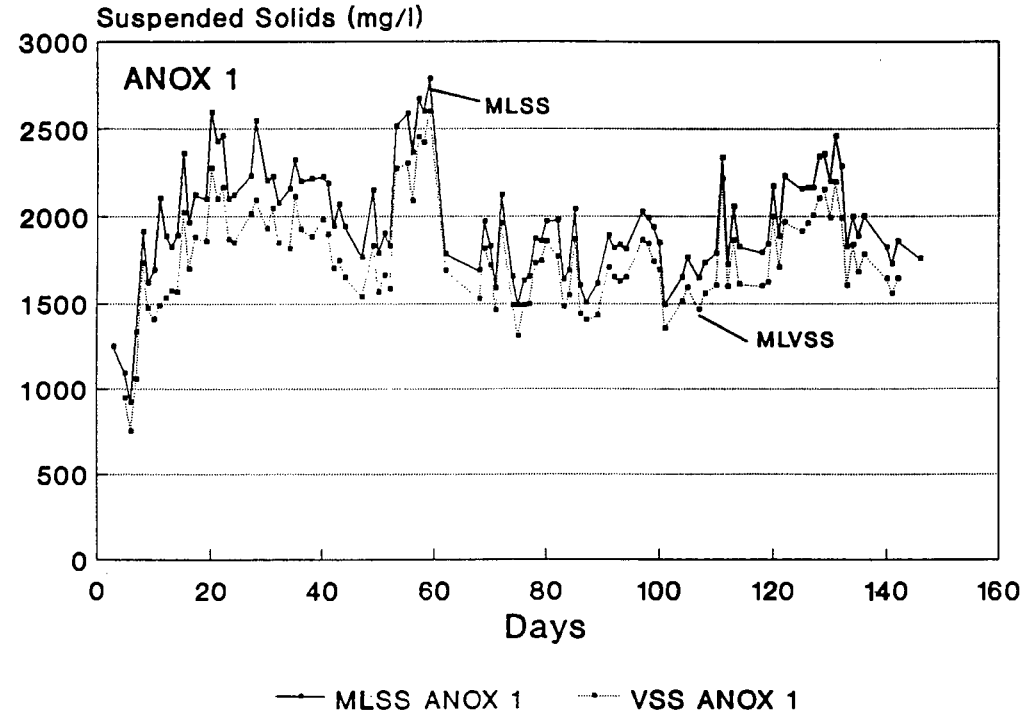



Fig 3.4 : Reactor MLSS and MLVSS concentration data measured daily on CFR 1 (a, top) and ANOX 1 (b, bottom) during phase 1 of the investigation.

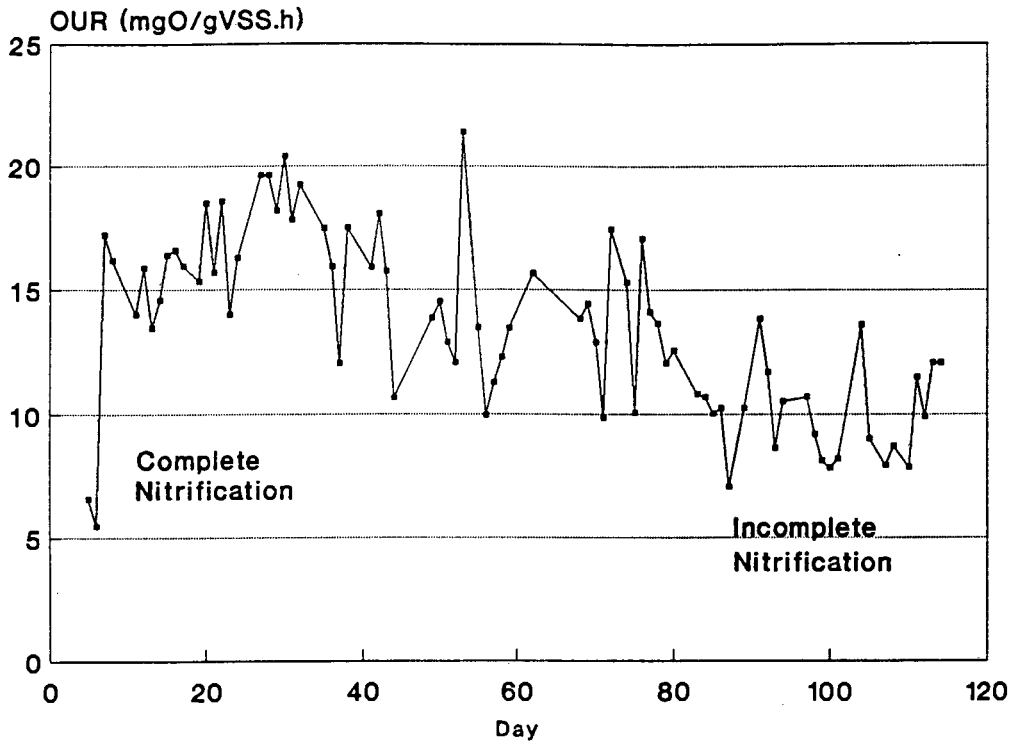



Fig 3.5 : Oxygen utilisation rate (OUR) per gVSS during aerobic cycle of CFR 1 during phase 1 of the investigation. The lower OUR from day 80–120 is due to nitrification no longer being complete (see effuent TKN, Fig 3.2) and is the reason nitrate was dosed from day 80 (see Fig 3.3a).

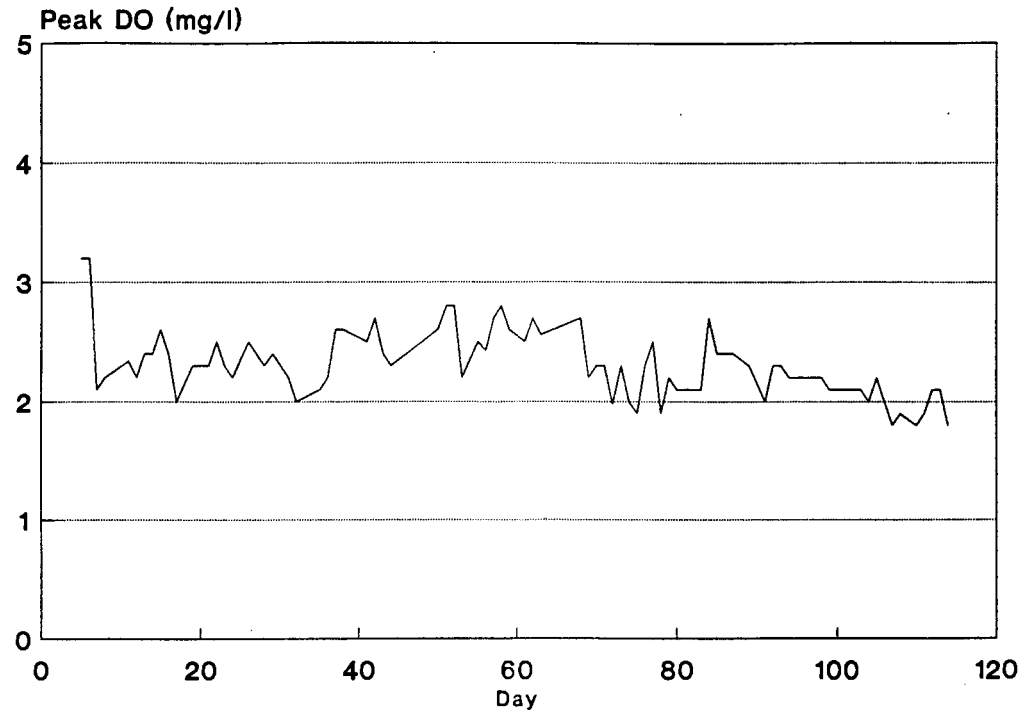



Fig 3.6 : Peak dissolved oxygen (DO) concentration (mgO/l) during intermittent aeration cycle measured daily on intermittent aeration cycle system CFR 1 during phase 1 of the investigation.

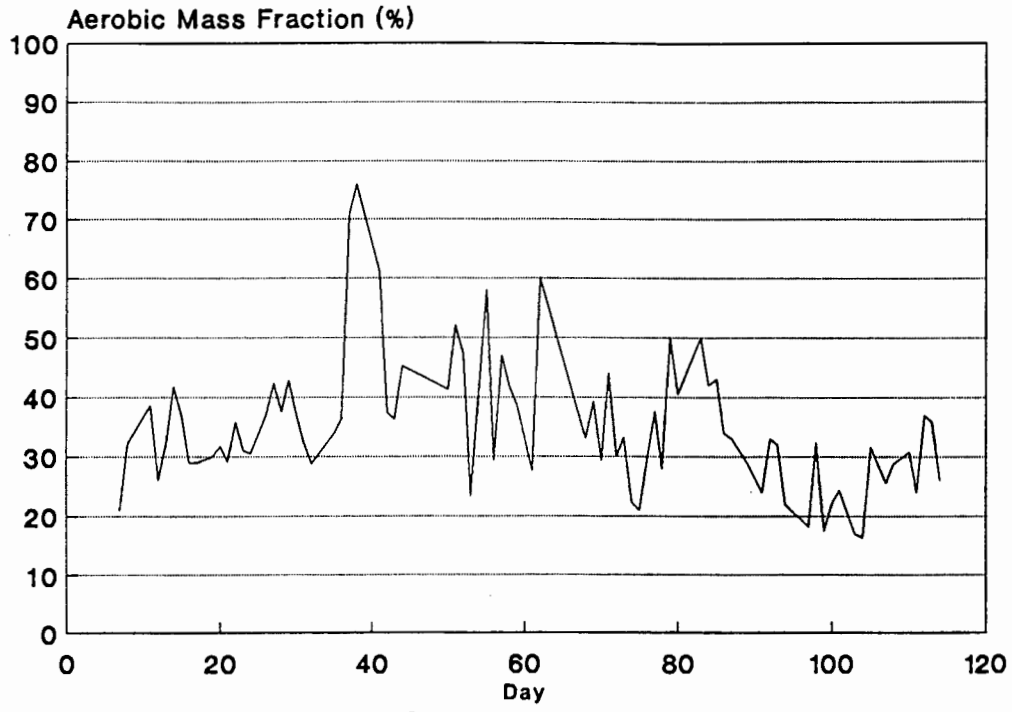



Fig 3.7 : Aerobic mass fraction measured daily on intermittent aeration cycle system CFR 1 during phase 1 of the investigation. The aerobic percentage was that fraction of the aeration cycle when the DO >0.2mg/l. The aerobic fraction decreased to between 20 and 30% between day 80 to 120, the probable cause for the incomplete nitrification during this period (see Figs 3.2 and 3.3).

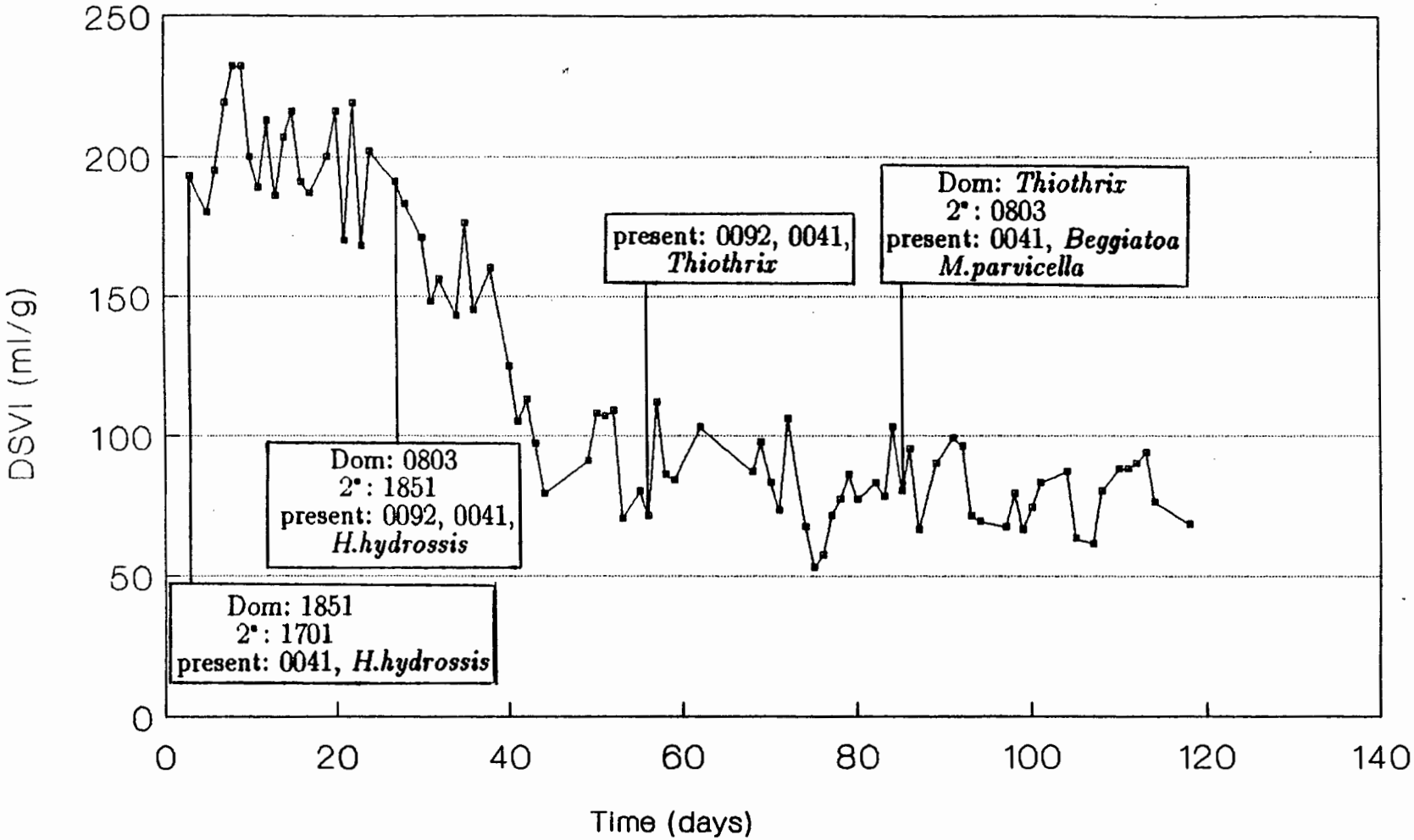



**Fig 3.8** : DSVI data measured daily on the intermittently aerated system CFR 1 during phase 1 of the investigation. Included on the graph are the filament identifications done and the days on which they were done.

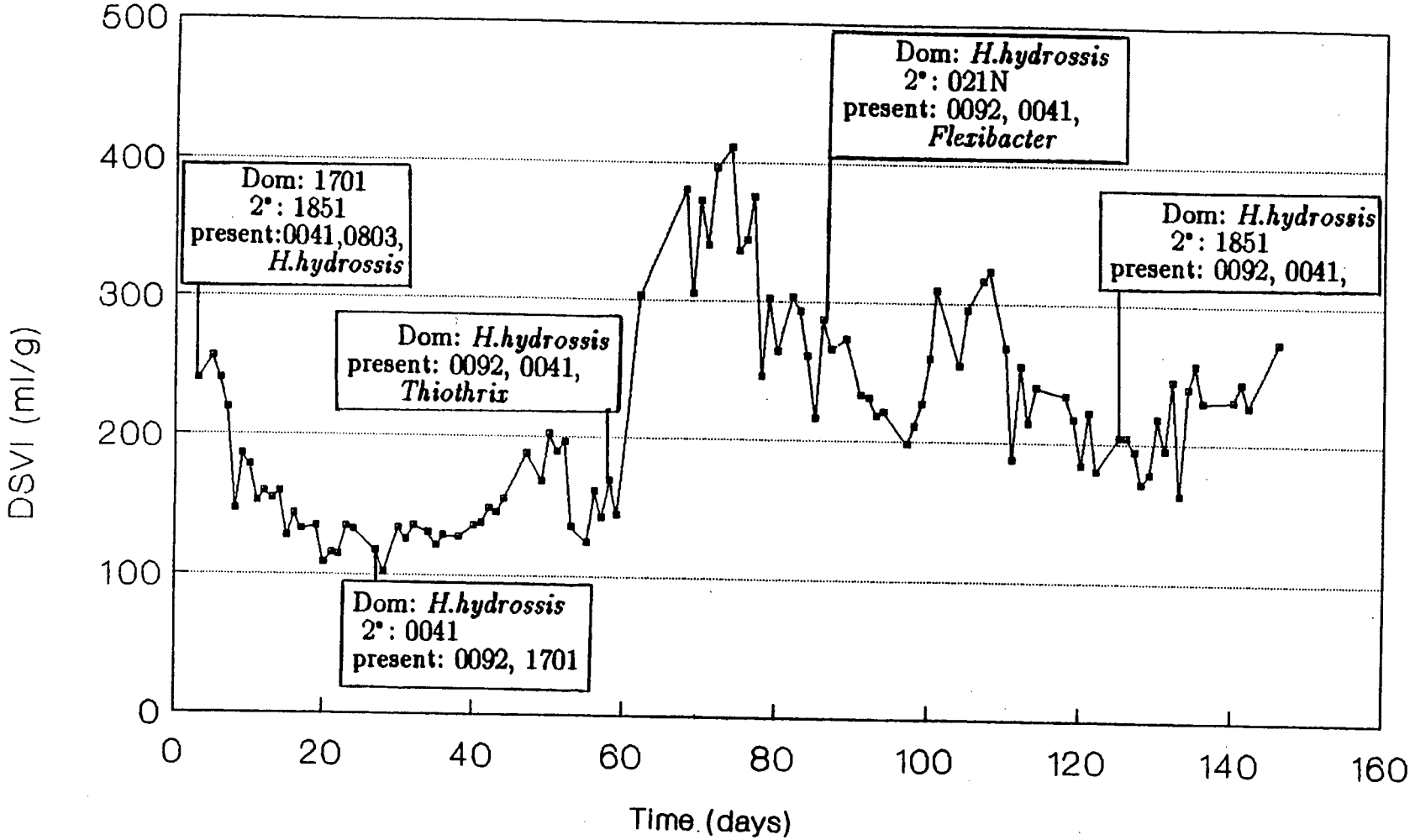



**Fig 3.9** : DSVI data measured daily on the fully anoxic system ANOX 1 during phase 1 of the investigation. Included on the graph are the filament identifications done and the days on which they were done.

latter is calculated from the sum of the masses of effluent COD, $M(S_{te})$, COD leaving the system in the waste sludge, $MS_{xw}$, and the mass of oxygen consumed during utilisation of COD under aerobic and anoxic conditions, $M(O_c)$. The influent and effluent COD and the VSS concentration in the reactor were measured daily and are presented graphically. The influent and effluent COD masses ($MS_{ti}$ and $MS_{te}$ respectively) are the products of the influent flow and the influent and effluent COD concentrations. The COD of the wasted sludge was calculated as the product of the mass of VSS wasted daily and the COD/VSS ratio of the sludge where the latter was assumed to be 1,48mgCOD/mgVSS and the former the product of the measured reactor VSS concentration and the volume of mixed liquor wasted daily. Thus the COD balance was calculated as follows:

$$\text{COD balance} = \frac{M(S_{te}) + M(S_{xw}) + M(O_c)}{M(S_{ti})} \times 100\ \%$$

In the intermittently aerated system CFR 1, the carbonaceous oxygen damand, $M(O_c)$, was calculated as follows:

$$M(O_c) = M(O_{tm}) + M(O_d) - M(O_n) \quad \text{(mgO/d)}$$

where

$M(O_c)$ =mass of oxygen required for COD utilisation

$M(O_{tm})$ =measured mass of oxygen consumed daily

$$= \frac{OUR.24.\%aerobic.V_p}{100} \quad \text{(mgO/d)}$$

where

OUR = measured oxygen utilisation rate [mgO/(l.h)]

$V_p$ = volume of reactor ($\ell$)

$M(O_d)$ =mass of oxygen recovered through denitrification (mgO/d)

$M(O_n)$ =mass of oxygen used for nitrification (mgO/d)

The measured OUR [mgO/(l.h)] was calculated from the dissolved oxygen (DO) concentration vs time curve measured during the aerobic period of the intermittent aeration cycle. The slope of the DO, measured as it decreased from its peak of

on other systems outside this investigation, where N balances could be determined, N balances better than 95% were achieved (Warburton *et al*, 1991). The operating and testing techniques used in the operation of CFR 1 were the same as on the other systems with good N balances and assumption 1 is therefore acceptable.

In assumption 2 the OUR throughout the aerobic period was accepted as constant. Thus the OUR was accepted to be the average slope of the DO concentration time curve between the peak DO (≃2.0–3.0mgO/l) and 0.5 mgO/l below which point the OUR often began to decrease (i.e. the slope began to flatten out). This decrease increased the aerobic period slightly but not significantly. The aerobic period was measured off the DO concentration time trace and was taken as the percentage of the the total aeration cycle during which the DO was greater than 0.2 mgO/l.

The above procedure was followed to calculate the COD balance for the CFR 1 system. The data measured over the 118 day phase 1 period were divided into 8 steady state periods, during each of which no major operational changes were made to the system which significantly affected the operation and hence the results. The periods and the COD balances achieved during these periods are given in Table 3.4.

To do a COD balance on the fully anoxic system ANOX 1 requires a somewhat different procedure to that of the intermittent aeration system CFR 1 developed above. Firstly, because the mass of nitrate denitrified, $M(N_{nd})$, can be calculated a N balance can be concluded and secondly $M(N_{nd})$ is directly proportional to the "oxygen utilisation" $MO_c$ ; because the system is fully anoxic $MO_c$ is equal to the oxygen recovered by denitrification $MO_d$. Hence

$$M(O_c) = M(O_d) = 2.86.M(N_{nd})$$

The nitrate denitrified $M(N_{nd})$ is simply the differemce between the influent and effluent nitrate masses, i.e.

$$M(N_{nd}) = M(N_{ni}) - M(N_{ne})$$

Table 3.4: COD balance results for experimental data obtained from system CFR 1 during phase 1. CFR 1 acted as a control system for the evaluation of the effect of fully anoxic conditions in ANOX 1. The effect of the nitrate concentration during the anoxic period was observed in system CFR 1.

| Period | Day to | Day | COD Balance (%)[1] |
|---|---|---|---|
| 1 | 0 | 15 | 64 |
| 2 | 16 | 30 | 61 |
| 3 | 31 | 45 | 62 |
| 4 | 46 | 60 | 60 |
| 5 | 61 | 76 | 70 |
| 6[2] | 77 | 89 | 68 |
| 7 | 90 | 105 | 72 |
| 8 | 106 | 118 | 73 |
| | | Average | 66 |

[1]Note : The N balance was assumed to be 100% for CFR 1.

[2]Additional nitrate bled into the system for periods 6, 7 & 8.

Having calculated $M(N_{nd})$, a N balance was performed by reconciling the total influent N (TKN and nitrate) with the total effluent N (TKN, nitrate and N in the waste sludge). The N balance was therefore

$$\text{N balance} = \frac{M(N_{nd}) + M(N_{ne}) + M(N_{te}) + M(N_w)}{M(N_{ni}) + M(N_{ti})} \times 100\ \%$$

Similar to CFR 1, the data measured on ANOX 1 over the 147 day phase 1 period was divided into 10 steady state periods, and the N balances calculated for these 10 periods varied between 87% and 93% with an average of 90% (Table 3.5). No reason for the slightly low N balances could be found. Knowing the equivalent mass of oxygen utilised, $MO_c$, the COD balance calculation for ANOX 1 is done in the identical way as that for CFR 1. COD balances obtained for the 10 steady state periods based on the $MO_c$ calculated from the measured $M(N_{nd})$ (i.e. 87%–93% N balance results) vary between 55 and 91% (see Table 3.5). COD balances were also calculated assuming a 100% N balance in order to examine the effect of the low N balances on the COD balance. With a 100% N balance $M(N_{nd})$ was recalculated as the difference between all the N inputs and outflows as follows

$$M(N_{nd}) = M(N_{ti}) + M(N_{ni}) - M(N_{te}) - M(N_{ne}) - M(N_s)$$

The COD balances for the 10 steady state periods assuming a 100% N balance are given in Table 3.5 and vary between 68% and 97%.

Accepting 100% N balances for both CFR 1 and ANOX 1, the COD balances obtained for CFR 1 varied from 60% to 73% with an average of 66% and for ANOX 1 varied from 55% to 91% with an average of 70%. These COD balances are low because generally COD balances of 95% or better are expected. Several explanations for the low COD balances obtained were proposed.

As stated in Table 3.3 problems were encountered from day 14 with the sludge blocking the overflow tube of system CFR 1. This occurred after the sludge flocs had become very granular in appearance, caused by the production of large amounts of polymeric material in the sludge, and during the slow movement through the overflow tube, they formed clumps which coagulated together and eventually blocked

Table 3.5: COD balance results for experimental data obtained from system ANOX 1 during phase 1. The system was operated fully anoxic and received a synthetic sewage feed throughout the experimental period.

| Period | Day | to | Day | N Balance (%) | COD Balance (%) |
|---|---|---|---|---|---|
| 1[3] | 0 | | 6 | | |
| 2 | 7 | | 29 | 92 | 55.1 |
| 3 | 30 | | 44 | 90 | 73.1 |
| 4 | 45 | | 55 | 89 | 55.1 |
| 5 | 56 | | 68 | 90 | 91.1 |
| 6 | 69 | | 84 | 87 | 78.3 |
| 7 | 85 | | 99 | 93 | 65.7 |
| 8 | 100 | | 114 | 89 | 70.1 |
| 9 | 115 | | 129 | 92 | 69.7 |
| 10 | 130 | | 147 | 91 | 67.4 |
| | | | | Average | 69.8 |
| 1 | 0 | | 6 | 100[4] | 90.3 |
| 2 | 7 | | 29 | 100 | 62.5 |
| 3 | 30 | | 44 | 100 | 82.8 |
| 4 | 45 | | 55 | 100 | 67.9 |
| 5 | 56 | | 68 | 100 | 96.8 |
| 6 | 69 | | 84 | 100 | 89.2 |
| 7 | 85 | | 99 | 100 | 71.0 |
| 8 | 100 | | 114 | 100 | 78.2 |
| 9 | 115 | | 129 | 100 | 76.2 |
| 10 | 130 | | 147 | 100 | 75.8 |
| | | | | Average | 79.1 |

[3]The system ANOX1 was intermittently aerated during the first 6 days of operation and therefore no nitrogen balance could be calculated for the system during period 1 (see method for the calculation of COD balance for CFR 1).

[4]A 100% N balance was assumed as discussed in the text.

the overflow tube at the overflow interface, and had to be unblocked physically. When the flow was interupted in this manner temporary increases in the reactor volume resulted as well as inconsistent flow through the reactor and secondary settler. These perturbations were far more exaggerated if the blockage occurred overnight and affected the OUR because of the inconsistent volume and concentration of sludge.

Some sludge was often lost from the CFR 1 system when the blockage was removed due to the rapid flow through the settler until a constant flow was restored again. This resulted in settler failure with sludge lost into the effluent. Even though sludge carried over into the effluent bucket was settled and returned to the system some sludge was unavoidably lost during this process because it was suspended in the effluent. Clogging occurred at DSVI's ranging from above 200ml/g to around 50ml/g. In the filament identifications done on days 26, 56 and 85 an increase in the polymeric material mentioned above was observed which became denser with time. This material caused the flocs to coagulate into large clumps in the system which could only be broken up by sieving the sludge.

The dense polymeric material associated with the sludge also caused problems in the settler because the sludge would sometimes coagulate into a gelatinous matrix through which the water could filter but no sludge could move. This resulted in the sludge accumulating in the settler and not being returned to the reactor in the sludge recycle which caused the MLSS (and VSS) in CFR 1 to decrease. Often the sludge had to be returned to the system by physically draining the settler and pouring the sludge back into the system. This caused variations in the OUR and the DSVI measurements both of which are very dependant on the reactor solids concentration. To reduce the impact of these effects the system was cleaned and the sludge sieved to break up clumps once or twice a week depending on the severity of the problem and the frequency of the blockages.

In addition to the problems encountered with the sludge blockages and operational problems in CFR 1 which probably contributed significantly to the low COD balances obtained in that system several other factors could also have affected the COD balance. It has been the experience in the laboratory that in intermittent aeration systems with large anoxic mass fractions (Warburton *et al*, 1991) that poor COD balances are obtained, which after careful examination cannot at this stage be ascribed to an error in the experimental procedure. This has also been observed in

Modified UCT systems which have anaerobic zones and invariably also large anoxic mass fractions. It is possible that in systems with large unaerated mass fractions, and therefore particularly for system ANOX 1, some of the stoichiometric constants accepted in the mass balance calculations, some of which were derived from purely aerobic conditions, do not apply to accurately assess the COD balances. Also with the artificial sewage feed, the systems are much more prone than with real sewage to losing COD by wall reactions and settlement in the influent feed drum and feed lines. While effort was made to feed settled PBCOD solids which had coalesced into lumps to the systems, and daily cleaning of the feed drums and lines, it is very likely that some COD was lost in this way. Casey *et al* (1990) in their systems fed the synthetic sewage had similar problems as these. Thus it is likely that the lower COD balances achieved in CFR 1 and ANOX 1 were caused by a number of factors with the blockages encountered in CFR 1 being one of the most important contributing factors in that system. COD lost in the feed drums and lines in this way with synthetic sewage would account for the lower COD balances than similar systems receiving real sewage feed (see phase 2 later and Warburton *et al*, 1991).

In conclusion, in the operation of CFR 1 and ANOX 1, no single major problem encountered during the experimental period could completely account for the low COD balances and although all experimental procedures have been thoroughly checked it was concluded that the operational problems and difficulties with experimental systems receiving synthetic sewage as well as the small aerobic mass fractions all contributed to the poor COD balances.

**System Behaviour – Low F/M filament Growth**

System CFR 1

At startup the sludge in CFR 1 had a DSVI of 190ml/g with the filaments 1851 and 1701 being dominant and secondary respectively (Fig 3.8). Other filaments present at this time were 0041 and *H.hydrossis* both at a tertiary level. The overall filament abundance was very common to abundant.

A filament identification done on day 26 with the DSVI at about 200ml/g showed that type 0803 had become dominant with 1851 decreasing to secondary. Type 1701 had disappeared and types 0092, 0041 and *H.hydrossis* were present at a tertiary level. The filament abundance had increased to the level of abundant to excessive

although the DSVI had remained similar to that at startup (i.e. in the range around 200ml/g). The presence of polymeric material was noted for the first time in this identification.

From day 26 the DSVI decreased to below 100ml/g by day 43. This decrease in DSVI was accompanied by a rapid reduction in the overall filament abundance and when a filament identification was carried out on day 56 few filaments were present with no dominant or secondary organism. Types 0092, 0041 and *H.hydrossis* were present at a low level only. An important observation was that the polymeric material was now observed as being dense.

From startup to day 53 the effluent nitrate from CFR 1 fluctuated from 2–15mgN/l, increases in the effluent nitrate concentration during this period were usually caused in variations in the aerobic mass fraction (Fig 3.7) for example between day 38 and 42 the aerobic mass fraction increased above 50% and the effluent nitrate increased during this period after which it reduced to less than 10 mgN/l again. A nitrate deficit occurs when there is insufficient nitrate to last for the whole anoxic period i.e. the nitrate concentration is reduced to zero before the end of the anoxic period. Warburton *et al* (1991) showed that a nitrate deficit could exist in an intermittently aerated system even though the effluent nitrate was still between 4 and 6 mgN/l due to the nitrate lost from the system during the aerobic period of the aeration cycle. From this it was accepted that a nitrate deficit existed in CFR 1 when the effluent nitrate was less than 8 mgN/l. The effluent nitrate concentrations up to day 53 show that the system was operating with a nitrate deficit during the anoxic periods except for the periods when the effluent nitrate was higher than about 8mgN/l, which was attributed to a higher aerobic mass fraction (which were directly correlated to changes in the OUR in the system). Thus up to day 53 it appeared that the nitrifying organisms in the sludge were supplying some nitrate to the anoxic period thereby ensuring some anoxic metabolism and denitrification but in the remainder of the anoxic period the system was nitrate deficient.

After day 53 up to day 78 the effluent nitrate concentration decreased to less than 2mgN/l. This indicated that there was very little nitrification taking place during the aerobic period, a consequence of the progressively decreasing aerobic mass fraction during this period (Fig 3.5). During this time the DSVI fluctuated but showed a decrease to about 65ml/g and the sludge became very dark grey in colour. This was seen as indicative of anaerobic or at least largely anaerobic conditions being

prevalent in the system during the unaerated period of the aeration cycle. The sludge also smelt sulphurous during this period. Also the filament identification done on day 83 showed that *Thiothrix*, a septic sewage filament, had become dominant in the sludge. These observations indicated that the system was operating under essentially aerobic/anaerobic conditions as opposed to the aerobic/anoxic/anaerobic conditions that were intended. Apart from the reduction in aerobic mass fraction the decrease in nitrification in CFR 1 could have been caused by the increase in the polymeric material surrounding the flocs which could have interfered with the diffusion of oxygen or nutrients into the flocs. If this happened then the nitrifying organisms might have been outcompeted for the oxygen and nutrients by the other organisms in the flocs. A similar scenario could also have caused or at least contributed to the reduction in the filament populations observed during this period.

As a result of the observation above that CFR 1 was operating largely anaerobically, nitrate was dosed to the system from day 78 until the experiment was terminated on day 118. Nitrate addition was started to see if filament growth could be stimulated (and a bulking sludge produced) in the sludge by ensuring aerobic/anoxic operation of the system. Nitrate was dosed directly into the reactor to maintain the effluent nitrate concentration at about 10mgN/l or above thus ensuring that the sludge did not become anaerobic during the anoxic period. Previously Gabb *et al* (1989a) and Casey *et al* (1990) had reported excessive growth of low F/M filaments in similar systems receiving synthetic sewage but their systems had started off with sludge already containing low F/M filaments and with DSVI's well above 120ml/g. Therefore it was unclear whether the low F/M filaments in CFR 1 would be able to recover after declining to the extent they had. The filament identification performed on day 85 showed *Thiothrix* dominant with type 0803 secondary and 0041, *Beggiatoa* and *M.parvicella* present at a tertiary level. The filament identification also showed that the polymeric material had now become very dense, an indication that the quality of the sludge was continuing to decline.

The reason why the sludge began producing the excessive polymeric material is unknown. These substances are produced in response to harsh environmental conditions. However once the sludge quality started to deteriorate it appears that this triggered the production of more and more polymers causing the sludge quality to continue deteriorating.

After three weeks of nitrate addition the sludge quality had not improved and blockages were occurring on a regular basis. Therefore in an attempt to improve the sludge quality and encourage low F/M filament growth the system was seeded with a bulking sludge (DSVI >150ml/g) from laboratory scale nutrient (N & P) removal MUCT systems on day 103 and 107. On these two occasions, a total of 2.5$\ell$ of sludge was discarded from CFR 1 and replaced with an equivalent volume of bulking sludge. The sludge that was added had type 0092 dominant. It was hoped that the addition of this sludge would increase the DSVI of CFR 1 to a value well above 100ml/g after which the filaments would proliferate as reported previously for similar systems by Gabb *et al* (1989a) and Casey *et al* (1990). However the addition of the bulking sludge had little affect on the settling characteristics of the sludge, the DSVI remained less than 100ml/g and blockages continued to occur frequently. Due to the unmanageability of the sludge and the absence of low F/M filaments in the sludge the experiment was terminated on day 118.

The decrease in low F/M filaments in the system with low nitrate levels in the anoxic period is consistent with observations by Casey *et al* (1990) using synthetic sewage in similar systems who noted a decrease in DSVI from 680–150 ml/g. They attributed the reduction in DSVI to the removal of *H.hydrossis* from dominance and the appearance of 1701 and 1851 which then caused an increase in DSVI again. Warburton *et al* (1991) using real sewage feed observed that lower nitrate concentrations depressed DSVI to a moderate extent, but their systems fed real sewage had *M.parvicella* dominant. In both instances the DSVI values remained above 150ml/g whereas the DSVI in CFR 1 decreased to well below 100ml/g. Gabb *et al* (1989a) found that when the synthetic sewage was fed to a MUCT system with a DSVI of ±190ml/g the DSVI decreased to around 80ml/g. The system was then seeded with bulking sludge for five consecutive days after which the DSVI again decreased to a low level. This behaviour is very similar to that observed in CFR 1 where seeding with sludge containing low F/M filaments did not prompt low F/M filament proliferation nor improve the quality of the sludge. The operational conditions in CFR 1 when it was operating aerobic/anoxic/anaerobic were similar to that of a MUCT system which has spatially separated aerobic/anoxic/anaerobic zones. Thus in some respects the conditions in the two systems were similar and so similar behaviour of the filamentous organisms could be expected. In CFR 1, 1851 and 1701 were dominant and secondary at startup and these filaments would have been expected to cause bulking from observations of these filaments in intermittent aeration systems with nitrate dosing by Casey *et al* (1990). Instead a change in the

filamentous population occurred with 0803 becoming dominant followed by a rapid decrease in the DSVI. It is possible that the production of the excessive amounts of polymeric material observed in the CFR 1 system was in some way linked to the rapid decrease in the low F/M filament populations in the sludge. It is unlikely that the synthetic sewage induced the production of the polymeric material because this phenomenon has not been observed before in similar systems receiving the same feed. It seems likely that the polymeric material was produced in response to the operation of the system at low nitrate levels in the anoxic period leading to longer anaerobic conditions which were not initially intended.

System ANOX 1

At startup the sludge in ANOX 1 had a DSVI of about 250ml/g with the filament abundance at the common level. Filament type 1701 was dominant with 1851 secondary. Other filaments present at a low level were 0041, 0803 and *H.hydrossis*. 1701 is a low DO filament (Jenkins *et al*, 1984) and it was expected that this filament would decrease under fully anoxic conditions. Therefore the main focus of the experiment was to observe the effect of the fully anoxic conditions on the growth of 0041, 1851, 0803 and 0092 (although not present at startup) i.e. the main causative organisms of low F/M filament bulking in Southern African nutrient removal activated sludge plants. *H.hydrossis*, although it is a low F/M filament is not often associated with low F/M filament bulking problems in full scale plants and therefore was not the main focus of the experiment.

From startup the DSVI decreased to a value of about 130ml/g by day 20 (Fig 3.9), after which it remained fairly constant until day 40. The lowest value recorded during this period was 102ml/g on day 28. A filament identification on day 26, DSVI about 120ml/g, showed that *H.hydrossis* had now become dominant with 0041 secondary. Type 0092 had appeared and was present at a low level together with 1701. The filament abundance was listed as abundant. Thus the filament abundance had increased from common at startup which was unexpected because the DSVI had actually decreased by more than 100ml/g during this period which would have been expected to be accompanied by a decrease in the overall filament abundance. This observation shows that the filament abundance, a subjective measurement, does not necessarily reflect the settling behaviour of the sludge because abundant filaments would be expected to be present only in a bulking sludge which was not the case in this instance.

The decrease observed until day 26 was attributed to the decrease of filament type 1701 in the sludge with it being present only at a low level as opposed to dominant at startup. This was expected as mentioned above as it is a low DO filament. The abundant filament abundance on day 26 was mainly attributed to the rapid growth of *H.hydrossis* to the dominant status in the sludge, indicating that this filament was best suited of the low F/M filaments present to the fully anoxic operating conditions. Type 0041, although it had increased in status to the secondary level, did not appear to have increased in number but rather maintained a similar level to that at startup and the other filaments had decreased relative to it. It is of interest to note that by day 26 types 1851 and 0803 had disappeared indicating their inability to grow under fully anoxic conditions. The appearance of 0092 at a low level indicated that this filament can grow in fully anoxic conditions but at this stage it was not contributing to bulking.

After day 40 the DSVI began to increase and by day 52 was around 200ml/g. A sudden decrease in DSVI from day 53–60 was caused by an increase in the MLSS (and VSS) during this period (Fig 3.4). The reason for the increase in DSVI after day 40 was the rapid proliferation of *H.hydrossis* which by day 56 was very markedly dominant with no secondary filament and the other filaments, 0092, 0041 and *Thiothrix* present only at a low level. This showed that *H.hydrossis* was able to proliferate excessively under fully anoxic conditions in a system receiving the synthetic sewage feed and that the other low F/M filaments were not as well suited to these conditions.

Up until day 56 enough nitrate had been added to the system to maintain the effluent nitrate concentration >20mgN/l. On day 57 the nitrate added to the system was reduced so that the growth of the filaments under low nitrate conditions could be observed. Due to the reduction in nitrate added to the system the effluent nitrate decreased to close to zero (Fig 3.3) on day 58 and remained low until day 67 when the nitrate feed was increased. During this period the system was running under partial nitrate deficient conditions and the sludge took on a dark grey colour indicative of anaerobic conditions, the system also smelt slightly sulphurous. During this period of partially anaerobic operation the DSVI increased dramatically to around 400ml/g due primarily to the growth of *H.hydrossis*. After day 67 when the amount of nitrate added to the system was increased again the effluent nitrate once again increased to above 20mgN/l. Although there were variations in the amount of nitrate added (Fig 3.3) from day 70 the effluent generally remained above 20mgN/l.

After the effluent nitrate concentration had increased on day 70 the DSVI decreased from around 400ml/g to between 200 and 300 ml/g and remained in this region for the rest of the experiment until day 147. The DSVI fluctuated considerably during this period, but the reasons for this could not be found.

Two filament identifications on days 85 and 124 showed that *H.hydrossis* was still dominant. On day 85 filament type 021N was secondary, the appearance of this filament was possibly due to the partially anaerobic functioning of the system until day 70 and it disappeared again when anoxic conditions were established again by high effluent nitrate levels. On day 124 type 1851 had reappeared as the secondary filament in the system. The reason for the appearance of this filament is unknown as it had disappeared from the system during the first 24 days of operation. Types 0092 and 0041 remained in the system at a low level for the the rest of the experiment (filament identifications on days 85 and 124) and this indicates that these two low F/M filaments are able to be sustained under fully anoxic conditions but not to the extent of causing bulking problems as they do in nutrient removal systems. *Flexibacter* is not a filament associated with bulking and therefore its appearance on day 85 and subsequent disappearance is unimportant.

From the results discussed above it was evident that the only filament that was able to proliferate to the extent of causing bulking under fully anoxic conditions in a system receiving the synthetic sewage as feed was *H.hydrossis.* The decrease in the DSVI in the first 30 days of operation was due to the decrease in abundance of type 1701 and the switch over to *H.hydrossis* being dominant. The subsequent increase in DSVI was evidently caused by the proliferation of *H.hydrossis* alone. Other low F/M filaments present, notably type 0092 and 0041, were able to grow in the system but not cause bulking. Due to the excessive growth of *H.hydrossis* but not other low F/M filaments the question arose as to whether *H.hydrossis* would proliferate to the same extent under fully anoxic conditions in a system receiving real sewage as feed. *H.hydrossis* is not one of the six low F/M filaments which cause the majority of bulking problems in full scale nutrient removal plants and in laboratory N and N&P removal plants. Therefore the experiment was terminated because it had shown that problematic organisms did not proliferate under these conditions and it was decided to repeat the experiment in similar systems receiving real sewage as feed. These systems are discussed in phase 2 below.

**Conclusions fron Phase 1**

1. In a fully anoxic system receiving synthetic sewage as feed the only low F/M filament that was able to proliferate to the extent of causing bulking was *H.hydrossis*. Other low F/M filaments present in the system were either unable to survive in the system, as in the case of 0803 and 1851, or were able to grow but not to the extent of causing bulking (types 0092 and 0041).

2. Low nitrate concentrations during the anoxic period of an intermittenly aerated system appear to inhibit the proliferation of low F/M filaments and lead to a reduction in the DSVI of the sludge. However the production of excessive amounts of polymeric material was also noted in this system which could have played a role in the reduction of the DSVI.

## 3.3 PHASE 2 THE EFFECT OF FULLY ANOXIC CONDITIONS ON THE GROWTH OF LOW F/M FILAMENTS IN CONTINUOUSLY FED COMPLETELY MIXED SINGLE REACTOR SYSTEMS RECEIVING REAL SEWAGE FEED

### 3.3.1 Experimental Set–up

In phase 1 it was observed that in ANOX 1 under fully anoxic conditions receiving synthetic sewage as feed only *H.hydrossis* grew excessively and caused bulking. Also in phase 1 initially the DSVI of the ANOX 1 sludge decreased to less than 150ml/g as all the filaments, apart from *H.hydrossis*, either decreased to a low level or disappeared from the system.

From these observations the question arose whether the low F/M filaments would behave the same way in fully anoxic systems receiving real sewage as feed. The reaction of *H.hydrossis* to fully anoxic conditions receiving real sewage as feed was also of interest because if this filament was unable to cause bulking when receiving real sewage as feed it would indicate that there was some nutrient in the synthetic sewage which *H.hydrossis* was able to utilise but that was absent in real sewage and which the other filaments were unable to use under continuous anoxic conditions.

This would indicate that the synthetic sewage was not representative of real sewage as far as the growth of low F/M filaments was concerned and therefore the use of the synthetic sewage should possibly be discontinued, at least in fully anoxic single completely mixed reactor systems. Therefore it was decided to operate similar systems to ANOX 1 but to feed them real raw sewage as opposed to the synthetic sewage used in phase 1. It was proposed to use (a) the sludge from ANOX 1 with *H.hydrossis* dominant in one system in order to observe the growth of this filament under fully anoxic conditions but now receiving real sewage feed and (b) a sludge with problem low F/M filaments (i.e. 0092 and/or 0041, etc.) dominant in another system. This would enable a comparison to be made with the behaviour of all the low F/M filaments observed previously during phase 1.

Two fully anoxic continuously fed single completely mixed reactor systems, ANOX 2 and ANOX 3, were started up with both systems receiving raw Mitchell's Plain sewage as feed. System ANOX 2 was system ANOX 1 of phase 1 ; the sludge in it was retained and the only change that was made was to swop the feed from synthetic to real sewage at the same COD concentration ( $\approx$ 500 mg/l). ANOX 3 was a system identical to ANOX 2 but seeded with sludge taken from laboratory scale NDBEPR nutrient removal systems with a DSVI at startup of about 150ml/g caused by the usual low F/M filaments causing bulking in these systems i.e. 0092, 0041, 0803 and 1851. Nitrate was dosed directly into both systems so that the effluent nitrate concentration was maintained at more than 20mgN/l to ensure that the systems were anoxic and did not become anaerobic at any stage. All holes and ports in the systems were sealed off to reduce the air movement above the mixed liquor in the systems and therefore reduce to a minimum the oxygen coming into contact with the liquid surface in the reactors. The monitoring and experimental procedures were the same as those used during phase 1 of the experimental investigation. The initial operating conditions and parameters for ANOX 2 and ANOX 3 are given in Table 3.6 and the changes that were made and operational problems encountered during the 44 day investigation period are listed in Table 3.7.

On day 19 an aerobic batch test was performed on combined sludge from the two systems, ANOX 2 and ANOX 3, and on day 42 anoxic and aerobic batch tests were performed on sludge taken from both systems. The aerobic batch tests were done to observe the oxygen utilisation rate in the sludge mass after extended exposure to anoxic conditions and to compare the rate of RBCOD utilisation measured in the sludge with those measured in sludge from aerobic and intermittently aerated

Table 3.6 : Initial operating conditions and parameters for the systems, ANOX 2 and ANOX 3, operated during phase 2. Both systems were fully anoxic systems receiving real sewage feed.

| System | ANOX 2 | ANOX 3 |
|---|---|---|
| Operating Conditions | Continuously Fed Completely Mixed Single Reactor | |
| Aeration | None | None |
| Sewage Source | Mitchell's Plain Raw | |
| Mass of COD fed/d | 5000 | 5000 |
| Volume of Feed (l/d) | 10 | 10 |
| Concentration (mgCOD/l) | 500-600 | 500-600 |
| Influent TKN (mgN/l) | 40-55 | 40-55 |
| Sludge Age (days) | 15 | 15 |
| Temp. (Deg C) | 20 | 20 |
| Reactor Volume (l) | 7.5 | 7.5 |
| pH of Mixed Liquor | 7.4-7.8 | 7.4-7.8 |
| Recycle Ratio | 1:1 | 1:1 |
| MLSS Conc. (mg/l) | 2000 | 2000 |
| VSS Conc. (mg/l) | 1800 | 1500-1800 |

systems. The anoxic batch tests were done to observe the rate of nitrate utilisation (i.e. the rate of RBCOD and PBCOD utilisation under anoxic conditions) in sludge maintained under fully anoxic conditions for an extended period and to see if the rates were different from previously measured rates in sludge taken from intermittently aerated systems [Warburton *et al* (1991)] and plug flow nitrogen removal systems (WRC, 1984). The methods employed for the batch tests (aerobic and anoxic) are set out in Appendix B.

### 3.3.2 Results and Discussion

The daily measured parameters made on the systems ANOX 2 and ANOX 3 during phase 2 are given graphically as follows :

Fig 3.10 Influent and effluent COD (unfiltered)
Fig 3.11 Influent and effluent TKN (unfiltered) (mgN/l)
Fig 3.12 Influent and effluent $NO_3$ (mgN/l)
Fig 3.13 Reactor MLSS
Fig 3.14 Reactor MLVSS
Fig 3.15 DSVI and filament identification

During the operation of ANOX 2 and ANOX 3 the effluent TKN concentrations were significantly higher than measured in aerobic/anoxic systems due to the lack of nitrification in ANOX 2 and 3. The influent nitrate concentrations varied considerably (Fig 3.12) up to day 20 due to problems encountered with the pump used to dose the nitrate to the systems. After day 20 the pump was replaced and the daily mass of nitrate dosed was more constant. The increase in the MLSS concentration of ANOX 3 up to day 10 (Fig 3.13) was because the system was started with a mass of sludge less than would be present in a system operating at a 15 day sludge age and it took 10 days for the steady state MLSS concentration to be reached.

**System Behaviour – COD Balance**

COD balances were calculated for ANOX 2 and ANOX 3 using the same method described for ANOX 1 in phase 1. The data for ANOX 2 and ANOX 3 was divided into 6 steady state periods (3 for each system). No significant changes were made to the systems during phase 2 and therefore the data was divided into sludge ages for the steady state periods i.e. 15 day periods. Because the mass of nitrate denitrified

Table 3.7 : Operational changes and problems for ANOX 2 and ANOX 3 during phase 2. Both systems were fully anoxic systems receiving real raw sewage feed. Unless specified changes made to both systems.

| Day | Change | Reason or Problem |
|---|---|---|
| 0 | Startup ANOX 2 and 3 | |
| 1 | | ANOX 2 : sludge in effluent replaced in system |
| 2 | ANOX 3 : Renew feed tube | Feed tube blocked |
| 11 | | $NO_3$ feed tubes blocked and low $NO_3$ feed. Therefore both systems anaerobic and effluents cloudy. |
| 12 | | Pump failure and no feed for several hours. |
| 14 | | Effluents cloudy due to anaerobic period on day 11. |
| 19 | Aerobic batch test done on combined sludge. | |
| 42 | Anoxic and aerobic batch tests done on sludge from both systems. | |
| 44 | Systems closed down. | |

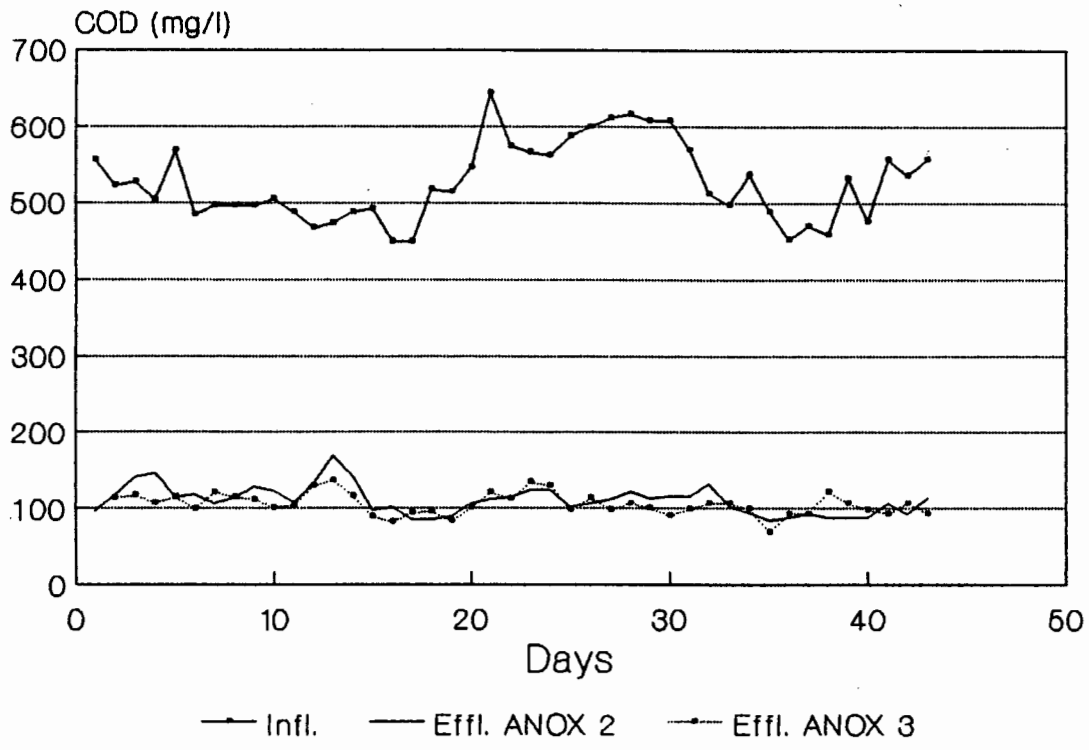



**Fig 3.10** : Influent and effluent (unfiltered) COD concentration measured daily for ANOX 2 and ANOX 3 during phase 2 of the investigation with both systems receiving real sewage.

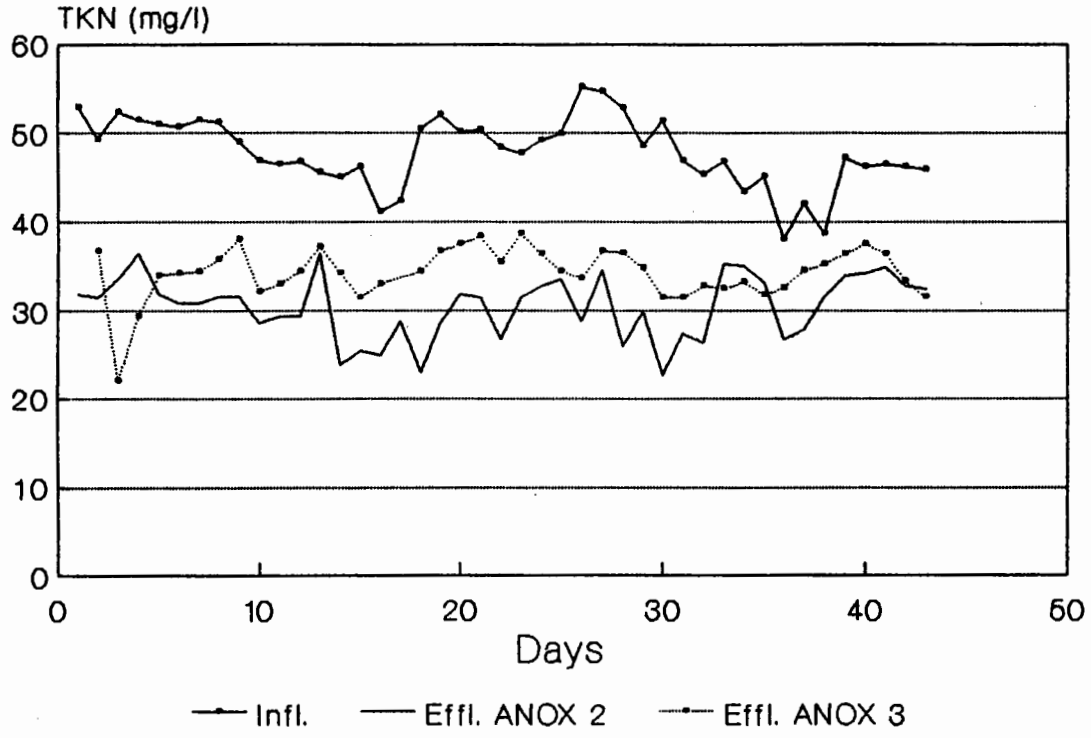



**Fig 3.11** : Influent and effluent (unfiltered) TKN concentration measured daily for ANOX 2 and ANOX 3 during phase 2 of the investigation with both systems receiving real sewage.

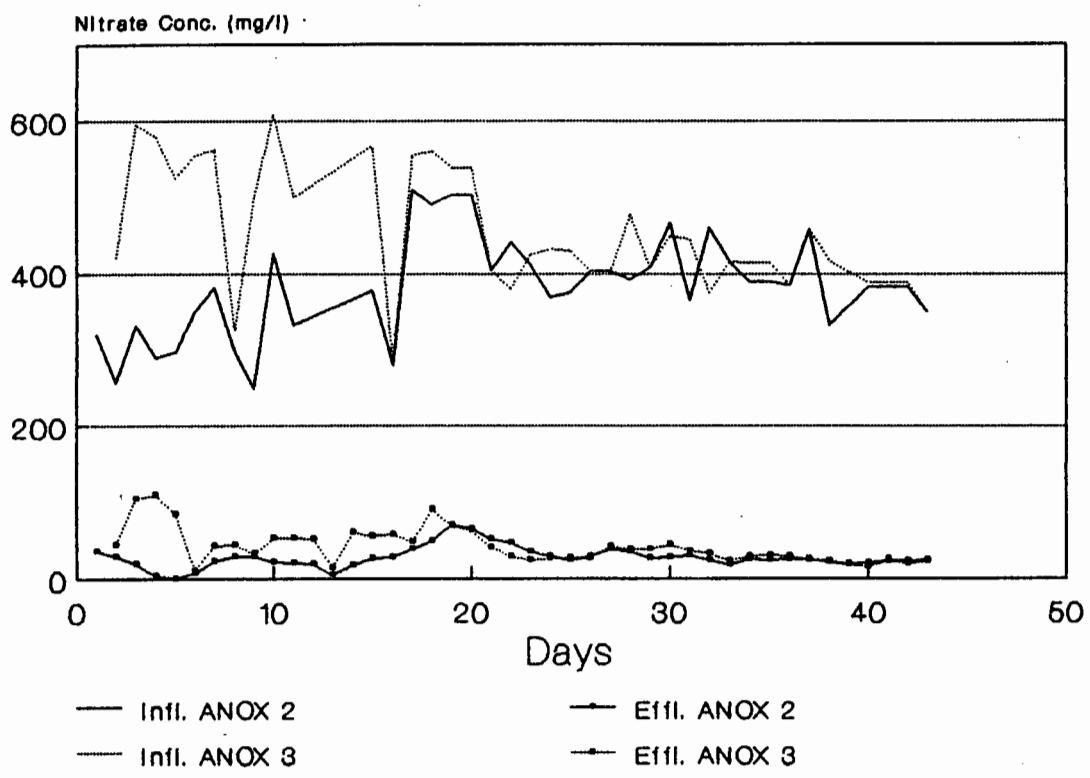



Fig 3.12 : Influent and effluent nitrate concentration measured daily for ANOX 2 and ANOX 3 during phase 2 of the investigation with both systems receiving real sewage.

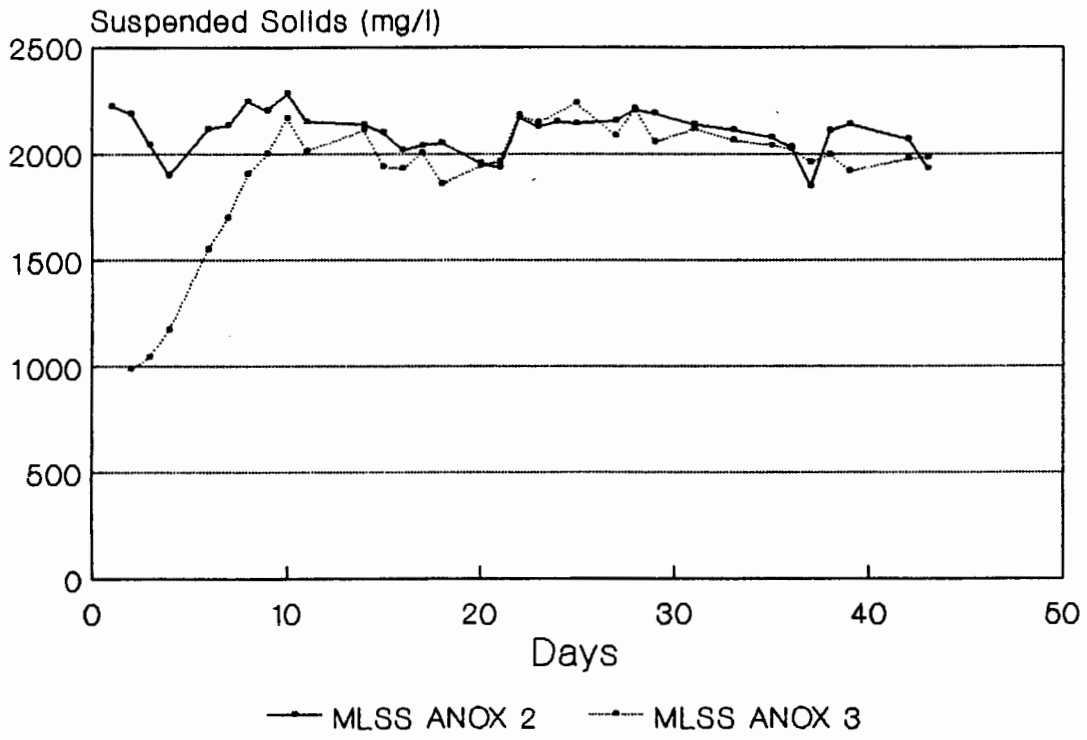



**Fig 3.13** : Reactor MLSS concentration data measured daily on ANOX 2 and ANOX 3 during phase 2 of the investigation.

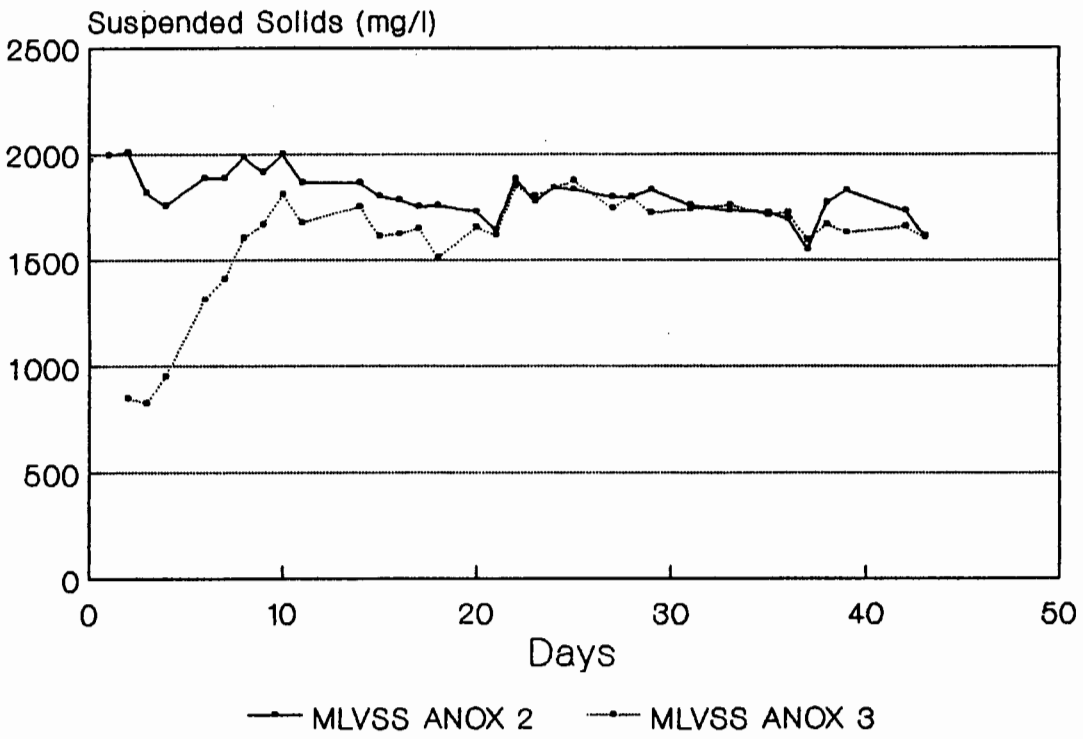



**Fig 3.14** : Reactor MLVSS concentration measured daily on ANOX 2 and ANOX 3 during phase 2 of the investigation.

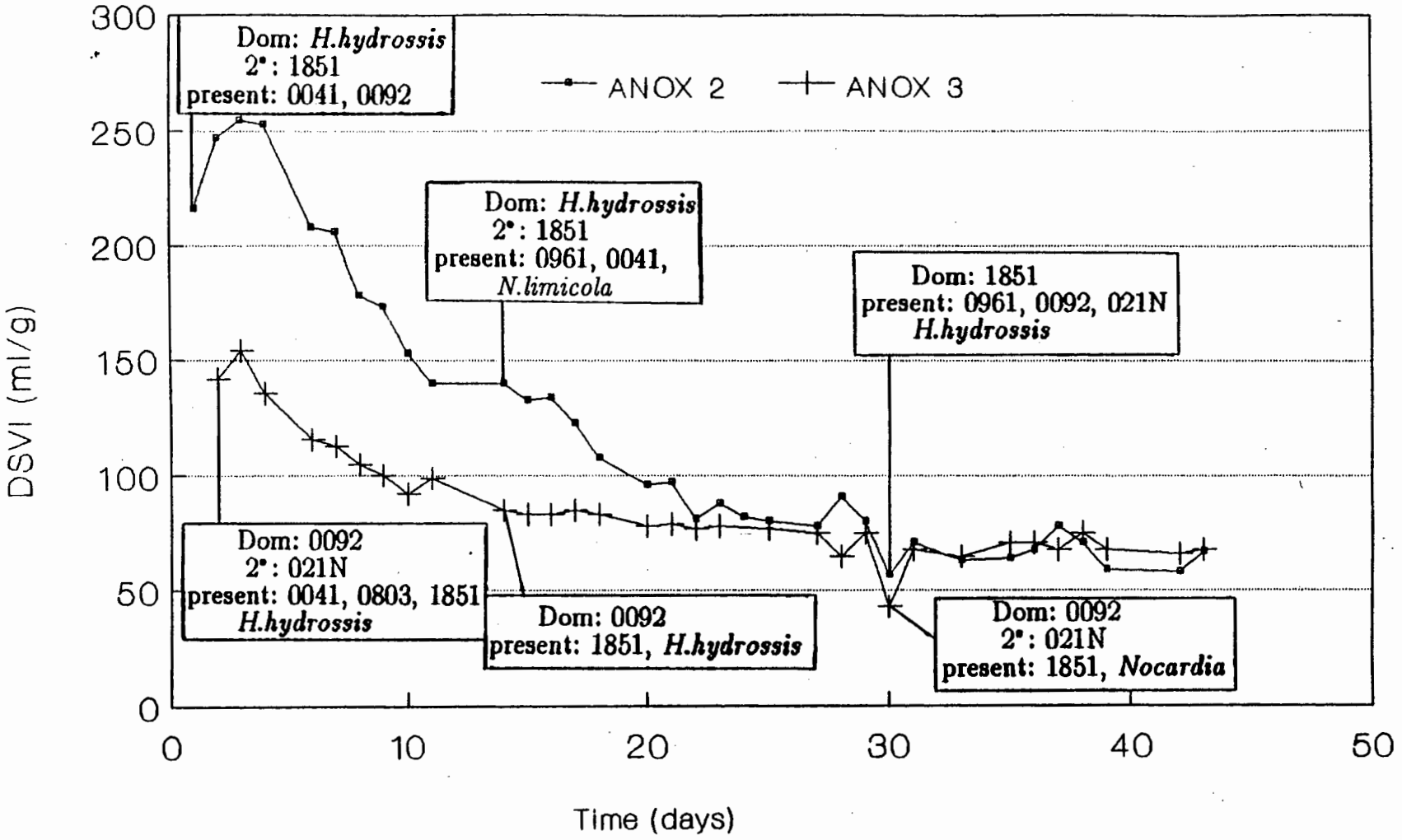



**Fig 3.15** : DSVI data measured daily on the fully anoxic systems ANOX 2 and ANOX 3 during phase 2 of the investigation with both systems receiving real sewage. Included on the graph are the filament identifications and the days on which they were done.

Table 3.8 : COD balance results obtained for ANOX 2 and ANOX 3 during phase 2 of the experimental investigation. Both systems fully anoxic and receiving real sewage feed.

| System | Period | Day to | Day | N Balance (%) | COD Balance (%) |
|---|---|---|---|---|---|
| ANOX 2 | 1 | 0 | 15 | 93 | 83 |
| | 2 | 16 | 30 | 93 | 71 |
| | 3 | 31 | 44 | 97 | 80 |
| ANOX 3 | 4 | 0 | 15 | 95 | 77 |
| | 5 | 16 | 30 | 95 | 72 |
| | 6 | 31 | 44 | 98 | 81 |
| | | | Average | | 77.2 |
| ANOX 2 | 1 | 0 | 15 | 100[1] | 88 |
| | 2 | 16 | 30 | 100 | 76 |
| | 3 | 31 | 44 | 100 | 82 |
| ANOX 3 | 4 | 0 | 15 | 100 | 81 |
| | 5 | 16 | 30 | 100 | 76 |
| | 6 | 31 | 44 | 100 | 82 |
| | | | Average | | 81.0 |

[1] N balance assumed to be 100% for the second set of COD balances as discussed in the text

could be calculated, the nitrogen balance also was checked. The N balances achieved ranged between 93% and 98% with an average of 95% (see Table 3.8). This was much improved and acceptably accurate compared to the 90% average achieved in ANOX 1 but it was still considered necessary to calculate COD balances assuming a 100% N balance (giving a slightly higher mass of nitrate denitrified, $M(N_{nd})$) as well as using the experimentally measured $M(N_{nd})$. The COD balances obtained in both cases are given in Table 3.8. The COD balances calculated using the measured $M(N_{nd})$ values ranged from 71% to 83% with an average of 77.2% whereas the COD balances assuming a 100% N balance ranged from 76% to 88% with an average of 81%.

The COD balances, like those in phase 1, are lower than would normally be expected for activated sludge systems operated under steady state conditions. Considering the fully anoxic operating conditions of systems ANOX 2 and ANOX 3 it is likely that the low COD balances are attributable to changes in certain kinetic parameters, such as the biological yield, ($Y_h$), and the endogenous respiration rate, ($b_h$), under the fully anoxic conditions. As discussed in phase 1 the values of these parameters were derived under fully aerobic or intermittently aerated conditions and have not been verified under fully anoxic conditions. The average COD balance obtained assuming a 100% N balance (i.e. 81%) is similar to that observed previously in intermittently aerated continuously fed single completely mixed reactor systems with a large anoxic fraction (Warburton *et al*, 1991) and this is an indication that the experimental procedures were not at error but that the low COD balances were caused by one of the factors mentioned above that was not taken into account in the COD balance calculations set out above. Apart from the factors mentioned above no explanation for the low COD balances could be found.

**Kinetic Performance of the Systems, ANOX 2 and ANOX 3**

A kinetic evaluation of the performance of systems ANOX 2 and ANOX 3 was carried out using two methods. Firstly the daily measured data was used to calculate the RBCOD loading rate and the PBCOD utilisation rate by applying the activated sludge steady state theory outlined in WRC (1984). For the purposes of doing this analysis the data was divided into the same steady state periods used for the COD balances discussed above. Secondly anoxic and aerobic batch tests were

conducted on sludge taken from the systems ANOX 2 and ANOX 3 and the RBCOD (under anoxic and aerobic conditions) and PBCOD (under anoxic conditions) utilisation rates measured under these conditions.

**Kinetic Evaluation of Daily Measured Data**

In the kinetic evaluation of the daily measured data from systems ANOX 2 and ANOX 3 the amount of nitrate denitrified, $M(N_{nd})$, in the systems (which was calculated for the COD balances) is used to calculate the rate at which RBCOD and PBCOD were utilised in the fully anoxic systems. The following kinetic parameters were calculated :

(1) Readily biodegradable COD (RBCOD) loading rate (RBCODLR) under anoxic conditions ($RBCODLR_{anx}$)

(2) Particulate biodegradable COD (PBCOD) utilisation rate (PBCODUR) under anoxic conditions ($PBCODUR_{anx}$).

The method for the calculation of the $RBCODLR_{anx}$ and $PBCODUR_{anx}$ is given in Appendix C and the COD utilisation rates calculated using this method are presented in Table 3.9. On analysis of the results in Table 3.9 it can be seen that the PBCOD utilisation rates are significantly higher than the RBCOD utilisation rates. This is because the RBCOD utilisation was restricted by the RBCOD loading rate i.e. the RBCOD is used up as fast as it is loaded onto the systems. The PBCOD utilisation rates are lower than values reported previously by Warburton *et al* (1991) who observed an average $PBCODUR_{anx}$ of around 40 mgCOD/(gAVSS.h) in intermittently aerated single reactor systems. This indicates that the rate of PBCOD utilisation under fully anoxic conditions is about 3/4 ths of that in similar systems which are intermittently aerated.

**Kinetic Evaluation of Batch Tests**

Anoxic Batch Tests

Anoxic batch tests were performed on sludge taken from ANOX 2 and ANOX 3 on day 42. In these batch tests, a measured mass of sludge was mixed with a measured mass of sewage COD and the nitrate concentration was measured regularly over the following 4 hours. Details of the equipment used and the methods followed during the anoxic batch tests are given in Appendix B. The nitrate concentration curves

Table 3.9: COD utilisation rates in mgCOD/(gAVSS.h) calculated for the experimental data measured during phase 2 on systems ANOX 2 and ANOX 3. The data was divided into the same steady state periods as used for the calculation of the COD balances for these systems.

| System | Period | $RBCODUR_{anx}$ [1] | $PBCODUR_{anx}$ |
|---|---|---|---|
| ANOX 2 | 1 | 5.68 | 31.13 |
| | 2 | 5.68 | 27.07 |
| | 3 | 5.68 | 32.60 |
| ANOX 3 | 1 | 5.68 | 30.02 |
| | 2 | 5.68 | 27.44 |
| | 3 | 5.68 | 32.83 |
| | | Average | 30.18 |

---

[1] – The values of RBCODUR are low compared to other values mentioned in the literature [Gabb *et al* (1989a)] but this is because the RBCODUR was limited by the RBCOD loading rate in the operaton of ANOX 2 and ANOX 3 whereas the rates given by Gabb *et al* (1989a) were measured under batch test conditions where the RBCOD concentration was not rate limiting.

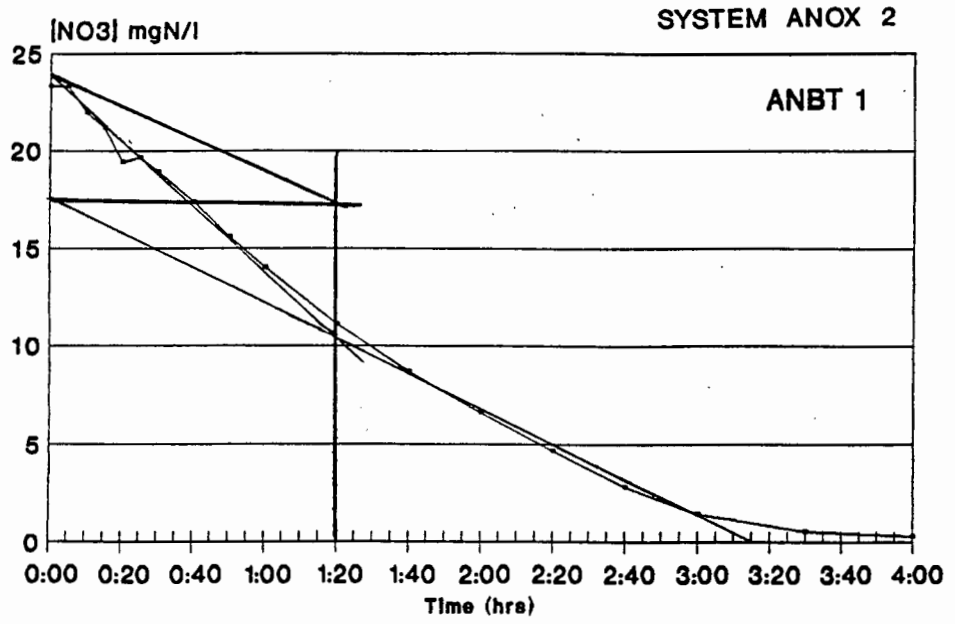
Table 3.10: Anoxic batch test conditions and dentirification rates calculated from the data measured during the anoxic batch tests ANBT 1 and ANBT 2 performed on day 42 using sludge from systems ANOX 2 and ANOX 3 respectively. Both systems were fully anoxic single completely mixed reactor systems receiving raw sewage as feed. Note : the values for $K_1$ and $K_2$ at the bottom of the table are the average values obtained by Ekama and Marais (WRC, 1984) used for the design of nitrogen removal activated sludge plants.

| Batch Test | ANBT 1 | ANBT 2 |
|---|---|---|
| Day | 42 | 42 |
| Parent System | ANOX 2 | ANOX 3 |
| VSS (mg/l) | 1166 | 1250 |
| AVSS (mg/l)* | 414 | 448 |
| Loading Rates : | | |
| (mgCOD/gVSS) | 305 | 298 |
| (mgRBCOD/l)** | 74.8 | 78.3 |
| Denitrification Rate Constants : | | |
| K1' (RBCODUR) | 29.2 | 36.1 |
| K2' (PBCODUR) | 33.2 | 29.8 |
| [mgCOD/(gAVSS.h)] | | |
| K1 (WRC, 1984) | 258 | |
| K2 (WRC, 1984) | 36.1 | |
| [mgCOD/(gAVSS.h)] | | |

* – The AVSS was calculated using an assumed value for fav = 0.40 (see appendix C)

** – The RBCOD concentration was calculated using a value of fbs = 0.21 [this value was measured using the method of Ekama *et al.*, (1986)]

(a)




(b)

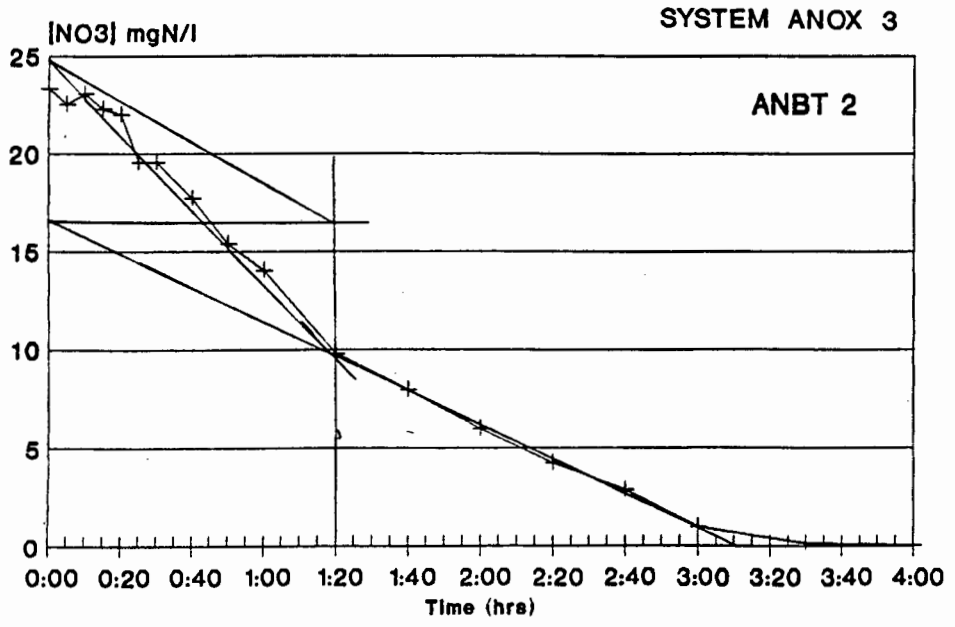



Fig 3.16: Nitrate concentration – time curves measured during the anoxic batch tests (a, top) ANBT 1 and (b, bottom) ANBT 2 using sludge from systems ANOX 2 and ANOX 3 respectively. On the graphs are marked the constructions used to calculate the two denitrification rates $K_1$ and $K_2$ (for RBCOD and PBCOD utilisation respectively). The method for the calculation of $K_1$ and $K_2$ is given in Appendix B.

conducted on combined sludge from ANOX 2 and ANOX 3 (1ℓ from each system), and on day 42 two further batch tests, ABT 2 and ABT 3, were performed using sludge from only ANOX 2 and only ANOX 3 respectively. The oxygen utilisation rates (OUR) in mgO/(gAVSS.h) measured during the aerobic batch tests 1 to 3 are given in Figs 3.17 and 3.18 (a and b) respectively. In Fig 3.18 the 0.45μm membrane filtered COD concentration profiles measured during ABT 2 and 3 are also plotted. The aerobic batch tests conducted on day 42 were done on the same batches of sludge used for the anoxic batch tests ANBT 1 and ANBT 2 discussed above; immediately after completion of the anoxic batch tests ANBT 1 and ANBT 2, the batch reactors were aerated and the OUR monitored.

The aerobic RBCOD utilisation rates ($RBCODUR_{aer}$) measured in the 3 aerobic batch tests are given in Table 3.11. The $RBCODUR_{aer}$ in ABT 1 was markedly lower than the rates measured in ABT 2 and ABT 3 (108 as opposed to 152 and 145). The reason for this probably was that in test ABT 1 (low $RBCODUR_{aer}$) aeration was commenced at the same time as the sewage was added to the batch reactor whereas in ABT 2 and 3 the mixed liquor was aerated for about 2 hours prior to the addition of the sewage. This aeration period prior to feeding possibly allowed the sludge bacteria to recover their aerobic metabolic capability which probably had become reduced due to the long exposure to fully anoxic conditions. In ABT 1 no such pre–aeration recovery period was incorporated with the result that the $RBCODUR_{aer}$ was lower while the aerobic capability of the sludge was recovering. Despite the possible need for a recovery period in ABT 1, the $RBCODUR_{aer}$ values measured in the aerobic batch tests are similar to values observed by Gabb *et al* (1989a) in sludge taken from intermittently aerated contiuously fed completely mixed single reactor systems. This showed that the aerobic metabolic capabilities of the sludge baterial populations (apart form the nitrifying organisms) is not significantly affected by the extended exposure to fully anoxic conditions. The $RBCODUR_{aer}$ values observed in the 3 batch tests were lower than those observed in *intermittently fed fill and draw* systems but this was expected because in these systems a rapid RBCOD uptake rate is induced by the intermittent feed pattern which is always higher than in continuously fed systems.

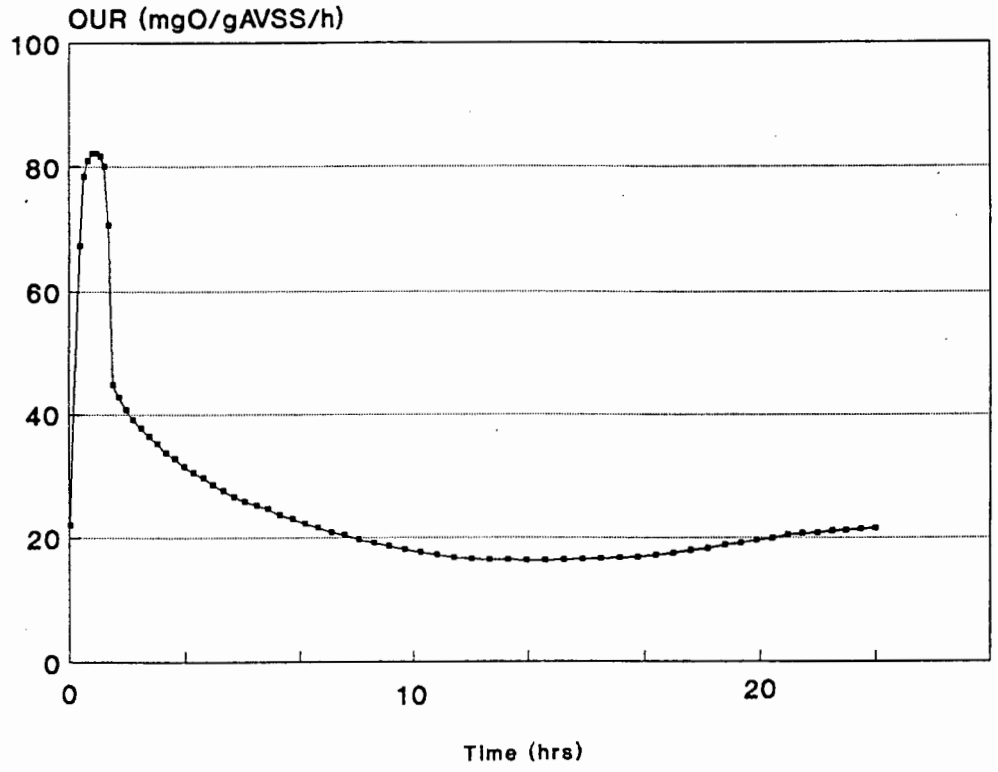



Fig 3.17: OUR profile measured during aerobic batch test 1, ABT 1, on combined sludge from systems ANOX 2 and ANOX 3. Both systems were fully anoxic single continuously fed completely mixed reactor systems.

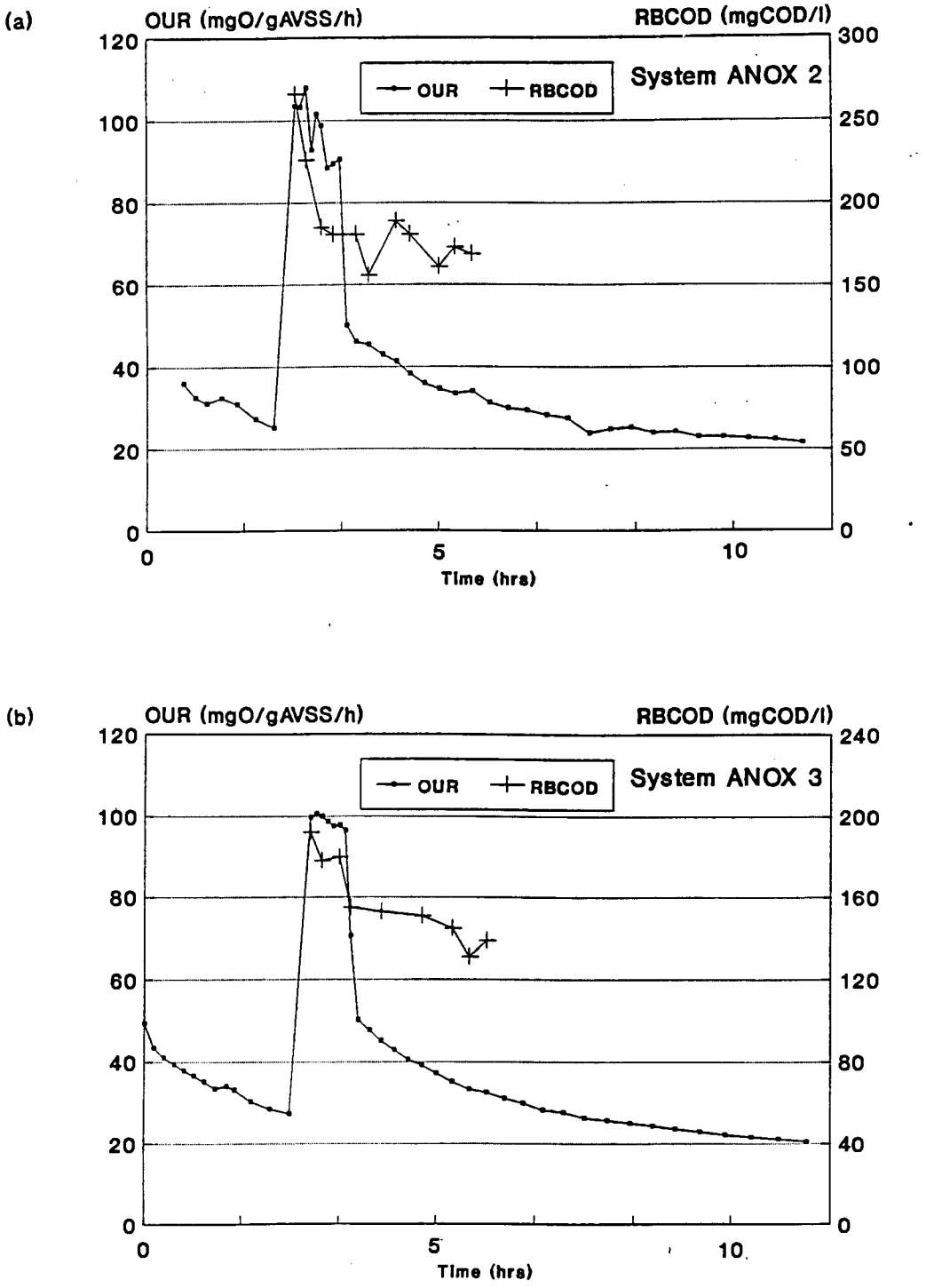



Fig 3.18: OUR profiles measured during the aerobic batch tests (a, top) ABT 2 and (b, bottom) ABT 3 conducted on sludge taken from fully anoxic systems ANOX 2 and ANOX 3 respectively. Also shown are the RBCOD concentration profiles during the tests taken from when the sewage was added to the batch test reactor vessels. The decline in OUR from time zero until sewage was added (about 130 minutes) is attributable to the utilisation of PBCOD on the sludge which was not utilised during the anoxic batch tests carried out on the respective sludges immediately prior to the aerobic tests.

Table 3.11: Aerobic batch test conditions and results for the batch tests ABT 1, ABT 2 and ABT 3 carried out on days 19 and 42 on sludge taken from ANOX 2 and ANOX 3, both fully anoxic continuously fed single completely mixed reactor systems receiving real sewage feed.

| Batch Test | ABT 1 | ABT 2 | ABT 3 |
|---|---|---|---|
| Day | 19 | 42 | 42 |
| Parent System | ANOX 2 & 3 | ANOX 2 | ANOX 3 |
| VSS (mg/l) | 1067 | 903 | 1036 |
| AVSS (mg/l)* | 427 | 361 | 414 |
| Loading Rates :<br>(mgCOD/gVSS)<br>(mgRBCOD/l)** | <br>322<br>72.3 | <br>413<br>78.3 | <br>360<br>78.3 |
| Aerobic<br>RBCOD Uptake Rate<br>(mgCOD/gAVSS.h) | 107.7 | 151.8 | 145.2 |

* – The AVSS was calculated using an assumed value for fav = 0.40 (see appendix C)

** – The RBCOD concentration was calculated using a value of fbs = 0.21 [this value was measured using the method of Ekama *et al.*, (1986)]

**System Behaviour – Low F/M Filament Growth**

At startup both systems contained bulking sludges with DSVI's of roughly 230 ml/g for ANOX 2 and about 150 ml/g for ANOX 3 respectively. Although both sludges were bulking sludges the filaments causing the bulking were markedly different due to the different starter sludges. In ANOX 2, which was started from ANOX 1 operated in phase 1 of this investigation, *H.hydrossis* was dominant with 1851 secondary, types 0041 and 0092 were present at a tertiary level (this was the sludge reatained from ANOX 1 in phase 1). In ANOX 3, started with MUCT NDBEPR sludge, types 0092 and 021N were dominant and secondary respectively with *H.hydrossis*, 0092, 0041 and 0803 all present at a tertiary level.

Despite the difference in DSVI and filament populations at startup, both systems showed a steady decrease in DSVI from day 3 and by day 20 the DSVI of the sludge in both systems had decreased to less than 100 ml/g. The sludge in ANOX 3 had attained a DSVI of less than 100 ml/g by day 14 but this was because this system had started at a lower DSVI than ANOX 2. A filament identification done on day 14 (Fig 3.15) showed that *H.hydrossis* and 0092 were still dominant in ANOX 2 and ANOX 3 respectively. Type 1851 was still secondary in ANOX 2 with types 0041, 0961 and *N.limicola* present at a tertiary level. No secondary filament was observed in the sludge on this day with only 1851 and *H.hydrossis* being present at a tertiary level. After day 20 the DSVI of both systems stabilised at a value of 60–80 ml/g for the remainder of phase 2. When the DSVI in ANOX 2 decreased to below 100 ml/g a filament identification done on day 30 showed that type 1851 had became dominant and that *H.hydrossis* had decreased to a large degree but was still present at a tertiary level. Also present at a tertiary level in ANOX 2 on day 30 were types 0961, 0092 and 021N. In ANOX 3 type 0092 remained dominant for the duration of phase 2 even though the DSVI decreased from 150 ml/g to around 70 ml/g. On day 30 type 021N was secondary in ANOX 3 with 1851 and *Nocardia* present at a low level.

The decrease in DSVI and in the dominance of *H.hydrossis* in ANOX 2 showed that the excessive growth of this filament in ANOX 1 during phase 1, when the system was fed the synthetic sewage, was not representative of the situation when real domestic sewage was used as feed. This proved that *H.hydrossis* was able to use one or more of the nutrients in the synthetic sewage which the other low F/M filaments were incapable of utilising under the fully anoxic conditions prevalent in ANOX 1.

Thus under the fully anoxic operating conditions the growth of the other low F/M filaments was the same as with real sewage but the excessive growth of *H.hydrossis* masked the overall decrease in DSVI which would have occurred in ANOX 1. This highlights the care that must be taken when using a synthetic sewage as feed for laboratory scale systems because the growth of a single organism can give greatly divergent results from what would happen in the real sewage situation. In both systems even though the DSVI decreased to well below 80 ml/g the filament abundance was still at the common to very common level which would not be expected for DSVI's in this range. This indicates that the low F/M filaments were able to be sustained to a moderate extent under fully anoxic conditions in continuously fed completely mixed single reactor systems but none of them were able to proliferate excessively to the extent of causing bulking under these conditions.

### 3.3.3 Conclusions for Phase 2

(1) Low F/M filaments were unable to proliferate to the extent of causing bulking in fully anoxic continuously fed single completely mixed reactor systems receiving real sewage as feed.

(2) The excessive growth of *H.hydrossis* under fully anoxic conditions in phase 1 was not a true reflection of that filament's growth under the same conditions receiving real sewage feed.

## 3.4 PHASE 3 THE EFFECT OF FREQUENCY OF ALTERNATION BETWEEN ANOXIC AND AEROBIC CONDITIONS ON LOW F/M FILAMENT BULKING IN INTERMITTENTLY AERATED CONTINUOUSLY FED COMPLETELY MIXED SINGLE REACTOR SYSTEMS RECEIVING REAL SEWAGE

### 3.4.1 Experimental Set–up

In phase 2 above it was observed that low F/M filaments were unable to proliferate in continuously fed completely mixed single reactor systems operated under *continuously anoxic* conditions receiving real sewage feed. Therefore it was evident that the severe low F/M filament bulking problems in *intermittently aerated* continuously fed single completely mixed reactor systems, as observed by Gabb *et al* (1989a) and Warburton *et al* (1991), it was not the anoxic or aerobic periods *per se* that caused the excessive growth of low F/M filaments but the alternation between these two conditions. Consequently it was proposed that in intermittent aeration systems, if very long aeration cycles were instituted, i.e. the frequency of alternation of the sludge to the respective anoxic and aerobic conditions was decreased, then the conditions in the mixed liquor would more closely resemble the fully anoxic and aerobic conditions. If this was so then the amelioration of low F/M filament bulking would occur and a strategy to control low F/M filament bulking in the intermittently aerated single reactor systems would be to increase the aeration cycle time.

To test this hypothesis, two intermittently aerated continuously fed single completely mixed reactor systems CFR 2 and CFR 3 were started up. The initial operating conditions and parameters for systems CFR 2 and CFR 3 operated in phase 3 are given in Table 3.12. The initial operating conditions of the systems were the same as those previously shown by Gabb *et al* (1989a) and Warburton *et al* (1991) to induce low F/M filament proliferaton on similar systems i.e. (i) long sludge age (15 days), (ii) small aerobic mass fraction (30%) (iii) nitrate addition and (iv) receiving real sewage as feed. Both systems were seeded with bulking sludge taken from the Mitchell's Plain full scale 4–stage Bardenpho activated sludge system which at the time had a DSVI of about 180ml/g caused by low F/M filaments (Fig 3.24). Initially both systems CFR 2 and CFR 3 were operated on short aeration cycles of between 15 and 30 minutes, depending on OUR, giving a frequency of exposure to both aerobic and anoxic conditions of 48 to 96 times per day. This initial period

served as a control to check that bulking occurred under these conditions as previously described (Gabb *et al*, 1989a, Warburton *et al*, 1991). Once the DSVI had been observed to increase under these short aeration cycle conditions the aeration cycle time was lengthened to reduce the frequency of alternation on a number of occasions ending with a maximum cycle of 3 days i.e. a frequency of 1 per 3 days. Throughout this phase of the investigation the aerobic mass fraction was maintained at 30%. Intermediate aeration cycle times investigated were 8h (3 cycles per day), 12h (2 cycles per day)and 24h (1 cycle per day).

After completing the investigation into the effect of the frequency of alternation, which took 215 days, system CFR 2 was changed to fully anoxic operation and system CFR 3 was changed to continuous aeration. These changes were made to check that the respective operating conditions (fully anoxic and continuous aeration) were effective in reducing the DSVI in the continuously fed completely mixed single reactor systems as had been observed previously in similar systems in phase 2 above, for fully anoxic operation, and by Gabb *et al* (1989a), for continuous aeration. The changes made to the aeration cycle of the two systems and any operational problems that affected the results obtained during phase 3 are presented in Table 3.13

### 3.4.2 Results and Discussion

The daily measured data from the systems CFR 2 and CFR 3 are given graphically in Figs 3.19 to 3.25 as follows :

Fig 3.19 Influent and effluent (unfiltered) COD (mg/l)
Fig 3.20 Influent and effluent (unfiltered) TKN (mgN/l)
Fig 3.21 Effluent nitrate (mgN/l)
Fig 3.22 MLSS and MLVSS for CFR 2
Fig 3.23 MLSS and MLVSS for CFR 3
Fig 3.24 The DSVI and filament identifications for CFR 2 and CFR 3 from day 0 to 130
Fig 3.25 The DSVI and filament identifications for CFR 2 and CFR 3 for day 130 to 241.

The OUR values measured on the systems during the aerobic period are not plotted

Table 3.12: Initial operating conditions and parameters for systems CFR 2 and CFR 3 operated in phase 3 of the investigation.

| System | CFR 2 | CFR 3 |
|---|---|---|
| Operating Conditions | Continuously Fed Completely Mixed Single Reactor | |
| Aeration | Intermittent | Intermittent |
| Aerobic Mass Fraction (%) | 30 | 30 |
| Aeration Cycle | 15-30 minutes | 15-30 minutes |
| Frequency of Alternation (/d) | 96 - 48 | 96 - 48 |
| DO Concentration | 0-2.5 | 0-2.5 |
| Sewage Source | Mitchell's Plain Raw | |
| Mass of COD fed/d | 5000 | 5000 |
| Volume of feed (l/d) | 10 | 10 |
| Concentration (mgCOD/l) | 500-600 | 500-600 |
| Influent TKN (mgN/l) | 40-60 | 40-60 |
| Sludge Age (days) | 15 | 15 |
| Temp. (Deg C) | 20 | 20 |
| Reactor Volume (l) | 7.5 | 7.5 |
| pH of Mixed Liquor | 7.4-7.8 | 7.4-7.8 |
| Recycle Ratio | 1:1 | 1:1 |
| MLSS Conc. (mg/l) | 3000 | 3000 |
| VSS Conc. (mg/l) | 2500 | 2500 |

Table 3.13 : Operational changes made to and problems encountered during operation of systems CFR 2 and CFR 3 during phase 3 with both systems intermittently aerated continuously fed single completely mixed reactor systems receiving real sewage.

| Day | Change | Reason or Problem |
|---|---|---|
| 0 | Startup systems | |
| 54 | Sludge from CFR 2 & 3 combined and then split. CFR 3 aeration cycle changed to 2 cycles/day (3.6 hrs aer. & 8.4 hrs. anoxic). | To ensure that both systems had identical sludge when the aeration cycle of CFR 3 was changed. |
| 67 | CFR 3 $NO_3$ feed reduced. | To reduce denitrification in settler. |
| 91–92 | | Sewage very sulphurous (septic). CFR 3 foaming caused by septic sewage |
| 108–17 | | CFR 2 settler failure. Sludge returned to system. Day 114–6 low $NO_3$ feed. |
| 118 | CFR 2 switched to continuous aeration (DO ≃ 0.5–2.0 mg/l). | To reduce DSVI to a level which could be contained in the system. |
| 119 | CFR 3 changed to 1 cycle/day 7.2 hrs. aerobic (DO 0.3–2.3 mg/l) & 16.8 hrs. anoxic) | |
| 131 | Renew $NO_3$ feed tube to CFR 2 | Tube split |
| 133 | CFR 2 changed to 1 cycle/day (DO 1.3–2.3 mg/l) CFR 3 changed to continuous aeration (DO 2–4 mg/l) | To reduce DSVI to a manageable level due to regular settler failure. |
| 137 | CFR 3 changed to 1 cycle/day (DO 0.3–2.3 mg/l) | To observe effect of longer aeration cycle on sludge with high DSVI |
| 158 | CFR 3 changed to continuous aeration. (DO 1.3–2.3 mg/l) | To reduce DSVI and prevent settler failure which occurred from day 154. |
| 161 | CFR 3 change DO to 2–4 mg/l | |
| 167 | CFR 3 change to 1 cycle/day | |
| 173 | CFR 2 change aeration cycle to 3 cycles/day & discontinue $NO_3$ feed. | To induce aerobic/anoxic/anaerobic conditions |

Table 3.13 : continued

| Day | Change | Reason or Problem |
|---|---|---|
| 182 | CFR 2 changed to continuous aeration | To reduce DSVI due to settler failure since day 179. |
| 183 | | Pump failure and no feed for several hours |
| 193 | CFR 2 changed to a 3 day cycle (21.6 hrs. aerobic & 50.4 hrs. anoxic). $NO_3$ feed begun. | To observe the effect of this long aeration cycle on the low F/M filament growth. |
| 199 | CFR 2 replace $NO_3$ feed tube. | Tube split overnight and system anaerobic for ±20 hrs. |
| 200 | CFR 3 changed to a 3 day cycle | To observe if the long aeration cycle has the same effect on sludge with a high DSVI as on sludge with a lower DSVI as in CFR 2. |
| 216 | CFR 2 changed to fully anoxic operation<br>CFR 3 changed to continuous aeration (DO 1.3–2.3 mg/l) | To verify that fully anoxic and fully aerobic conditions are effective in reducing bulking |
| 217 | | Powercut for 5 hrs and very weak sewage fed. |
| 218 | | CFR 3 aeration switched off overnight. |
| 221 | CFR 2 $NO_3$ feed concentration increased because sludge smelling sulphurous indicating partial anaerobism. | |
| 222 | CFR 3 add more buffer to influent sewage. | To increase pH to above 7.4. |
| 223 | | Pump failure and no feed for 20 hrs. |
| 232 | CFR 3 closed down. | Target DSVI reached. |
| 241 | CFR 2 closed down | Target DSVI reached. |

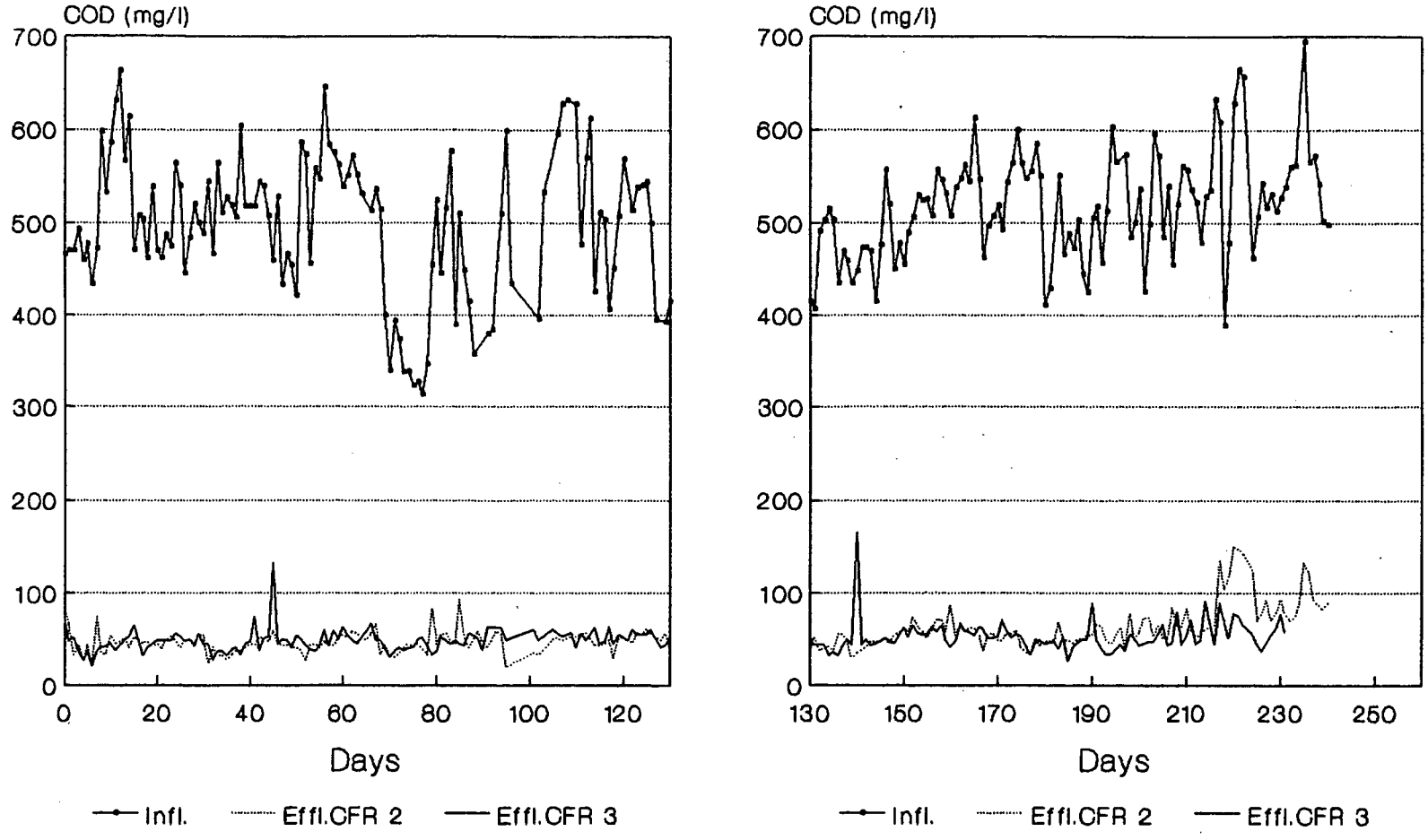



**Fig 3.19** : Influent and effluent COD data measured daily on CFR 2 and CFR 3 during phase 3 of the investigation.

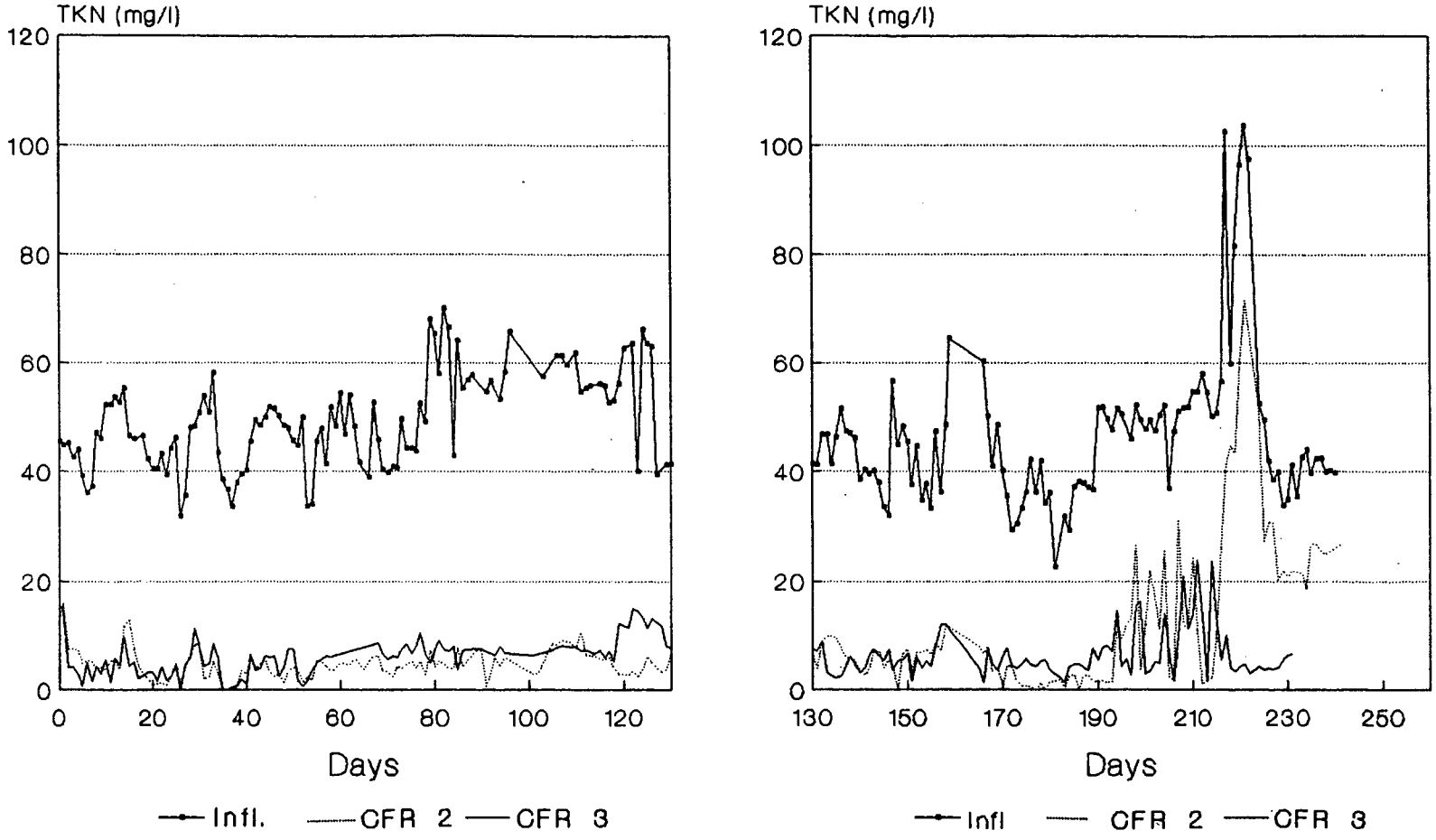



**Fig 3.20** : Influent and effluent TKN data measured daily on CFR 2 and CFR 3 during phase 3 of the investigation.

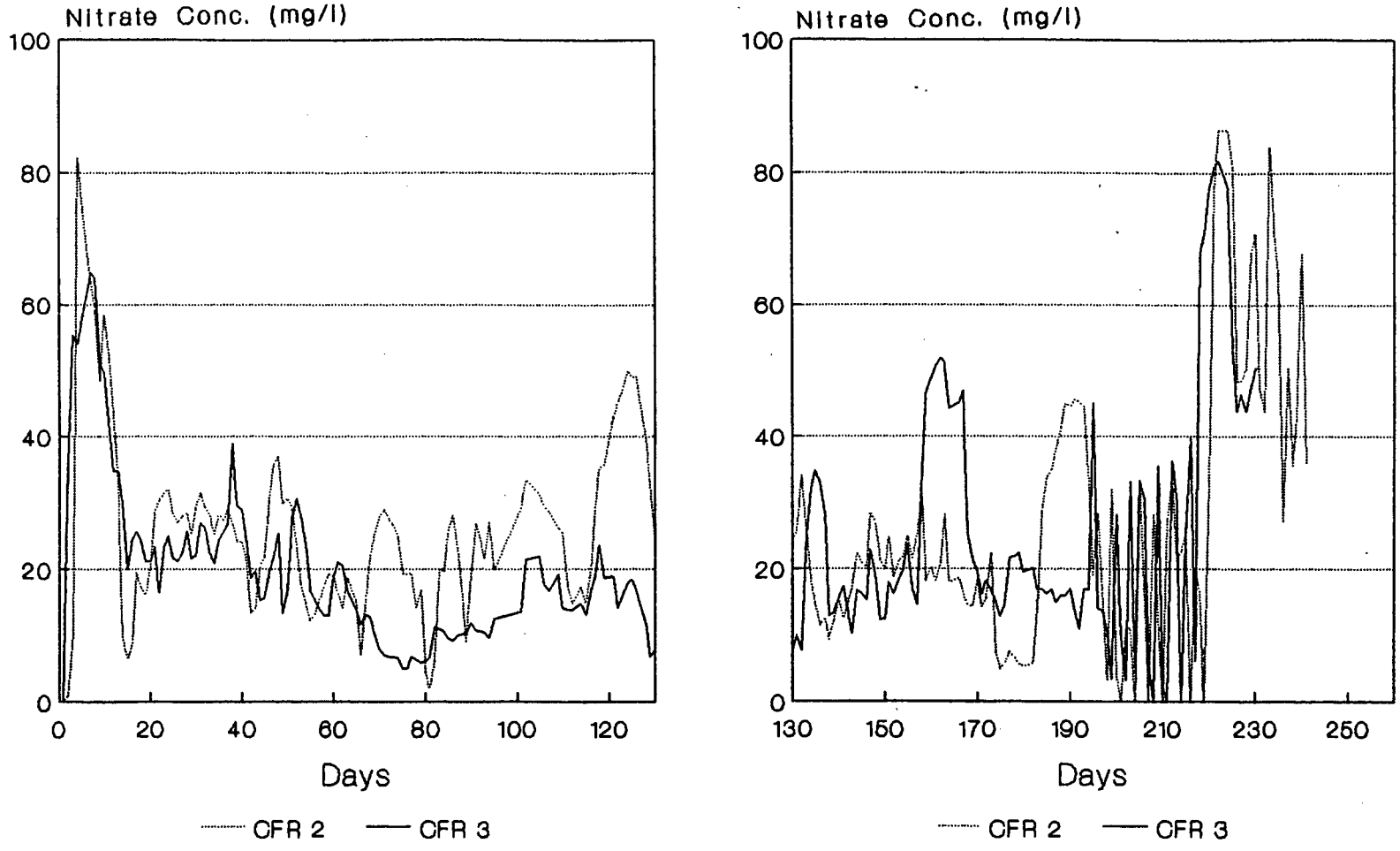
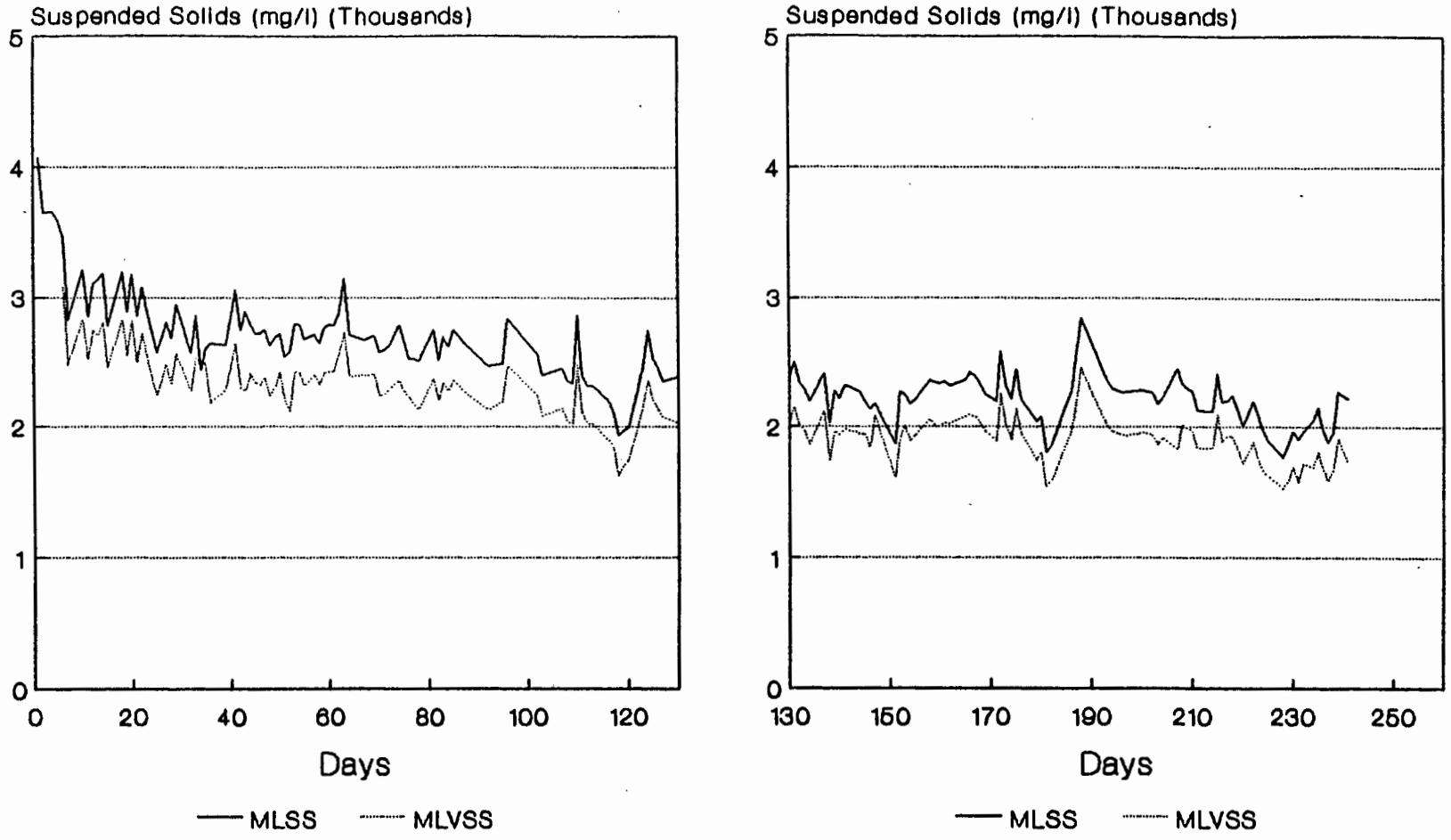



**Fig 3.21** : Effluent nitrate concentration data measured daily on CFR 2 and CFR 3 during phase 3 of the investigation.




<u>Fig 3.22</u> : Reactor MLSS and MLVSS concentrations measured daily on CFR 2 during phase 3 of the investigation.

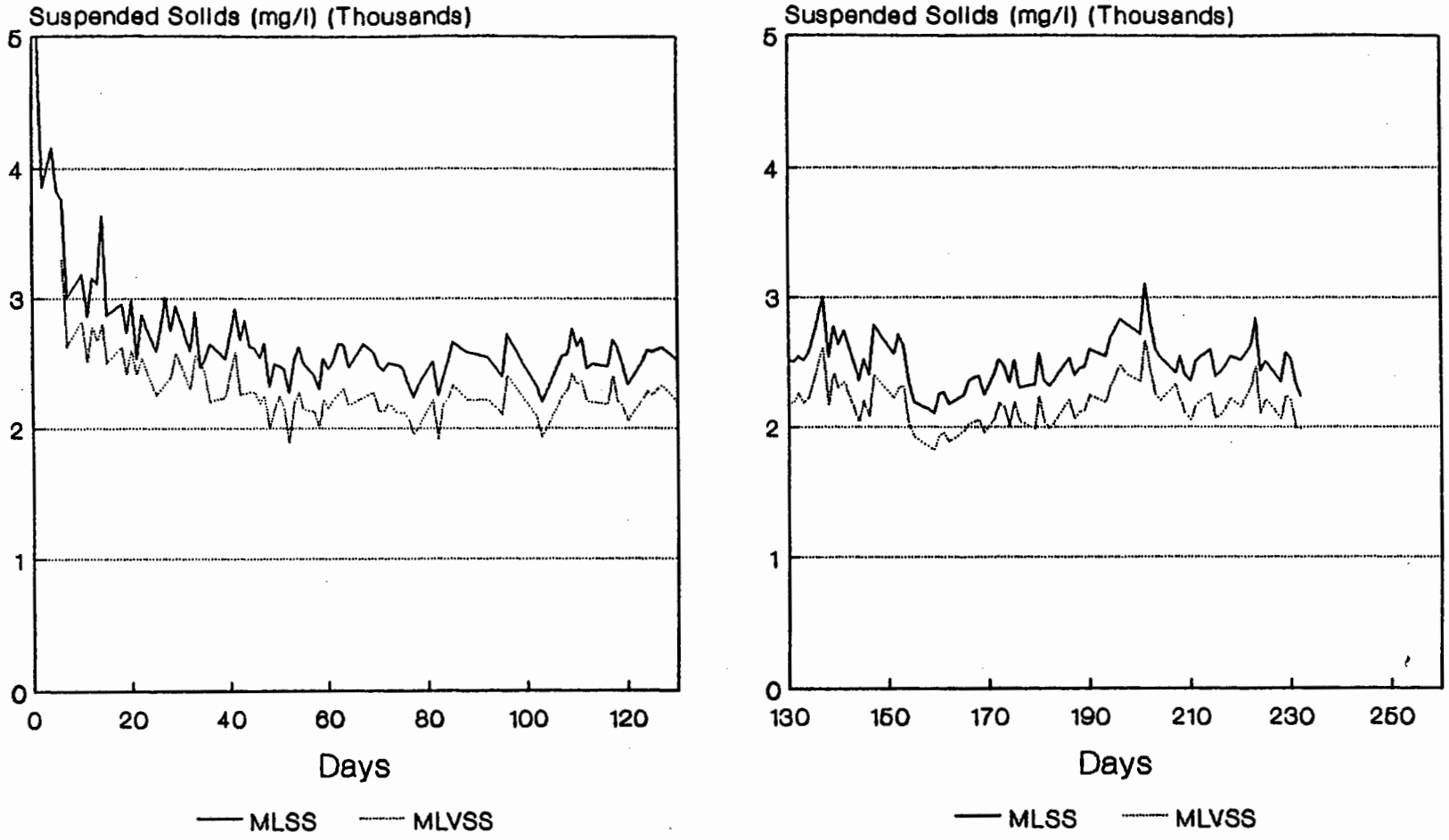
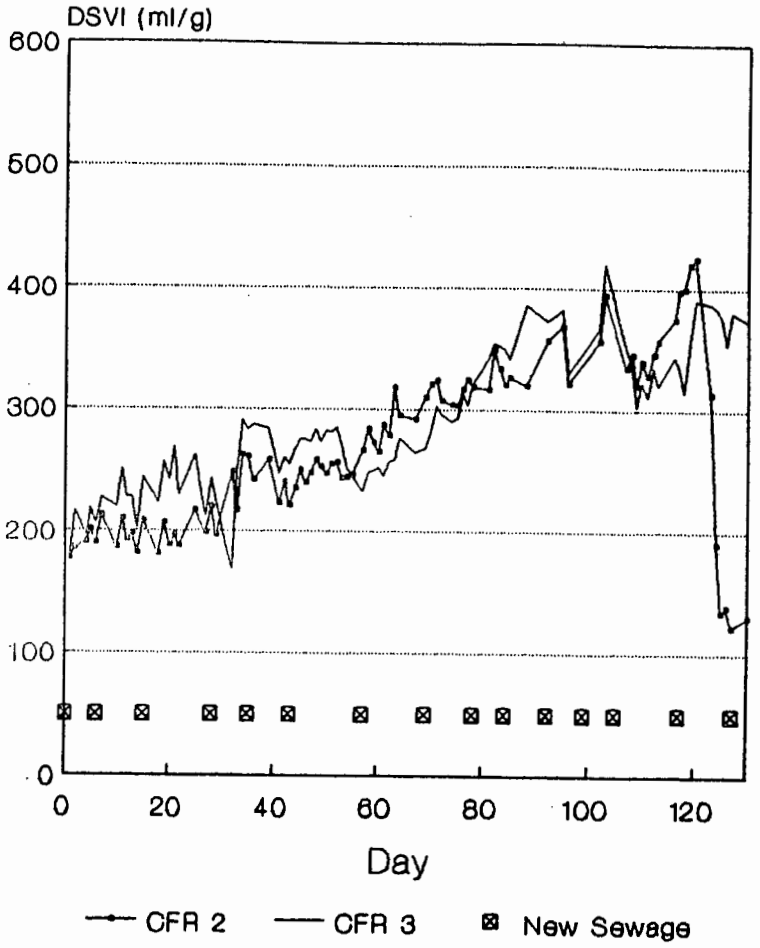



**Fig 3.23** : **Reactor MLSS and MLVSS concentrations measured daily on CFR 3 during phase 3 of the investigation.**

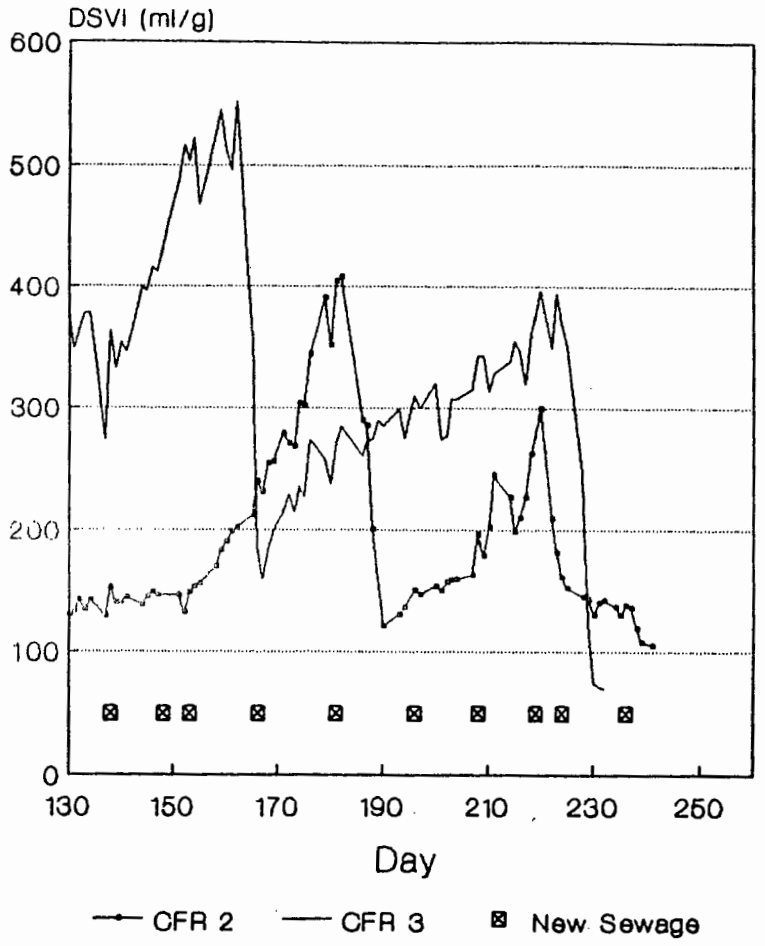



FILAMENT IDENTIFICATION

| Day | Unit | Abundance | Dom. | Sec. | Other |
|---|---|---|---|---|---|
| 13 | CFR 2 | Common - V. Common | Noc. | 0092 | H.hyd.<br>0041<br>021N |
| | CFR 3 | V.Common | 021N | Noc.<br>0092 | H.hyd.<br>0041<br>1851 |
| 28 | CFR 2 | V.Common-Abundant | 021N | 0092 | Noc. , H.hyd.<br>1851 , 0041<br>M.parv. |
| | CFR 3 | V.Common | 0092 | 021N<br>Noc. | H.hyd., 0041<br>1851<br>M.parv. |
| 43 | CFR 2 | Abundant | 021N | 0092 | Noc. , H.hyd.<br>0041 , 1851<br>0961 , M.parv. |
| | CFR 3 | Abundant | 021N | 0092<br>Noc. | 0041<br>1851 |
| 75 | CFR 2 | Abundant | 021N | 0092<br>M.parv. | 0041<br>1851<br>0961 |
| | CFR 3 | V.Common | 021N | M.parv. | 0041 , 0092<br>1851 |
| 102 | CFR 2 | V.Common-Abundant | 021N | M.parv. | 0092 , H.hyd.<br>0041<br>1851 |
| | CFR 3 | V.Common | 021N | 0092<br>M.parv. | 1851<br>0041 |

M.parv. - Microthrix parvicella
Noc. - Nocardia sp.
H.hyd. - Haliscomenobacter hydrossis

**Fig 3.24** : Daily DSVI data measured on CFR 2 and CFR 3 from day 0 to day 130 during phase 3 of the investigation. The filament identifications done and the days on which they were done are given in the table on the right hand side.




FILAMENT IDENTIFICATION

| Day | Unit | Abundance | Dom. | Sec. | Other |
|---|---|---|---|---|---|
| 133 | CFR 2 | V.Common | M.parv. | 0041 | 0092 ,H.hyd. 021N 0961 |
| | CFR 3 | Abundant | M.parv. | 021N | 0092 ,0041 1851 |
| 160 | CFR 2 | Abundant | M.parv. | 021N | Thio. ,0092 H.hyd. |
| | CFR 3 | Abundant | M.parv. | 021N | 0961 ,0041 1851 ,0092 |
| 193 | CFR 2 | Common - V.Common | M.parv. | 0961 | H.hyd. 0092 0041 |
| | CFR 3 | Common - V.Common | M.parv. | 0092 | Thio. ,H.hyd. 0961 ,1851 0041 |
| 216 | CFR 2 | V.Common | 0803 | 0092 | Thio. ,021N M.parv. 0961 |
| | CFR 3 | V.Common | M.parv. | 0092 1701 | Thio. 0041 |
| 241 | CFR 2 | Common | 0092 | M.parv. | 021N 0041 |

M.parv. - Microthrix parvicella
H.hyd. - Haliscomenobacter hydrossis
Thio. - Thiothrix sp.

<u>Fig 3.25</u> : Daily DSVI data for the period day 130 to 241 during phase 3 of the investigation. Filament identifications for the corresponding period are given in the table.

because when the systems were operated with aeration cycles longer than 30 minutes in length it was observed that the OUR decreased considerably during the first 2 to 4 hours after the system became aerobic due to the progressively decreasing utilisation rate of the ammonia and particulate biodegradable COD (PBCOD) accumulated during the anoxic period. Consequently not much store can be placed on the OUR data measured during the aerobic period insofar as calculating COD balances and steady state conditions are concerned nevertheless the OUR values measured during phase 3 are given in the data presented in Appendix F.

Several times during phase 3 the DSVI of the sludge in a system reached such a high value (usually above 380 ml/g) that settler failure occurred because the sludge could not be contained within the systems. When this happened the system was changed to continuous aeration, a condition known to ameliorate low F/M filament bulking (Gabb *et al*, 1989a). Continuous aeration was instituted to reduce the DSVI in the systems to a level at which the sludge could be contained within the system. When settler failure occurred the sludge in the effluent was settled out and returned back into the system although when this was done some sludge mass was invariably lost with the effluent.

Systems CFR 2 and CFR 3 were continuously dosed with nitrate throughout phase 3 except during the periods when the systems were continuously aerated. The large variations in effluent nitrate concentrations (Fig 3.21) were often caused by the changes made to the aeration cycles of the systems. When the systems were aerated continuously (e.g. CFR 2 between day 118 and 130) the effluent nitrate increased markedly due to the absence of denitrification of the nitrate produced by the nitrifiers. Also when the systems were operated on a 3 day aeration cycle, the effluent nitrate concentration changed markedly from day to day depending on the phase of the cycle, as happened between day 195 and 216 (Fig 3.21).

**System Performance – COD Balance**

COD balances were conducted on the daily measured data from systems CFR 2 and CFR 3 using the method described in phase 1 for system CFR 1. However due to the second assumption that is made in that method, i.e. that the OUR is constant throughout the aerobic period, COD balances could not be calculated for the periods when the aeration cycle was longer than 30 minutes. This was because when the aeration cycle was longer than 30 minutes (i.e. 12 hours, 24 hours and 72 hours) the

OUR changed during the aerobic period, as illustrated in Fig 3.26. The reason for the change in OUR over the aerobic period was that ammonia and PBCOD in the influent accumulate in the reactor liquid and the biological sludge during the anoxic period due to an absence of nitrification and a reduced PBCOD utilisation rate and causes a high OUR when the reactor becomes aerobic. When the accumulated ammonia and PBCOD has decreased considerably the OUR decreased to a level associated with the steady state nitrification and carbonaceous oxygen demand in keeping with the incoming ammonia and influent COD. Thus to accurately determine the OUR for long aeration cycles the OUR would have to be monitored throughout the aerobic period which was beyond the scope of the experimental procedures employed in this investigation.

Due to this COD balances were only calculated for the periods when the aeration cycle was less than 30 minutes where the OUR during the aerobic period is relatively constant and for the periods when the systems were fully aerobic and fully anoxic. The data from these periods was divided into 11 steady state periods (4 periods for intermittent aeration, 5 periods for continuous aeration and 2 periods for fully anoxic operation) during which no major changes were made which would affect the results. The COD balances calculated are presented in Table 3.14.

The COD balances achieved by the systems when intermittently aerated range from 66% to 84% which are lower than would be expected for these systems which usually achieve COD balances of around 85% (Warburton *et al*, 1991). The reason for the low COD balances during the intermittently aerated periods is unknown. When the systems were continuously aerobic the COD balances achieved were a lot higher with an average of 92% and a high of 98.3%. This indicates that the experimental procedures were acceptably accurate. The 2 low COD balances achieved in CFR 3 under fully aerobic conditions (Table 3.14) were probably attributable to instability in the system after the previous operating conditions where settler failure had occurred and the system MLVSS concentration was too low. N balances were also calculated for the continuously aerated periods and an average of 98% was achieved (see Appendix I), indicating that the experimental procedures were acceptably accurate.

The COD balances achieved in system CFR 2 for the fully anoxic periods at the end of the experiment are lower than those observed in ANOX 2 and ANOX 3 during phase 2. The low COD balance during period 6 of 65.5% was probably caused by the

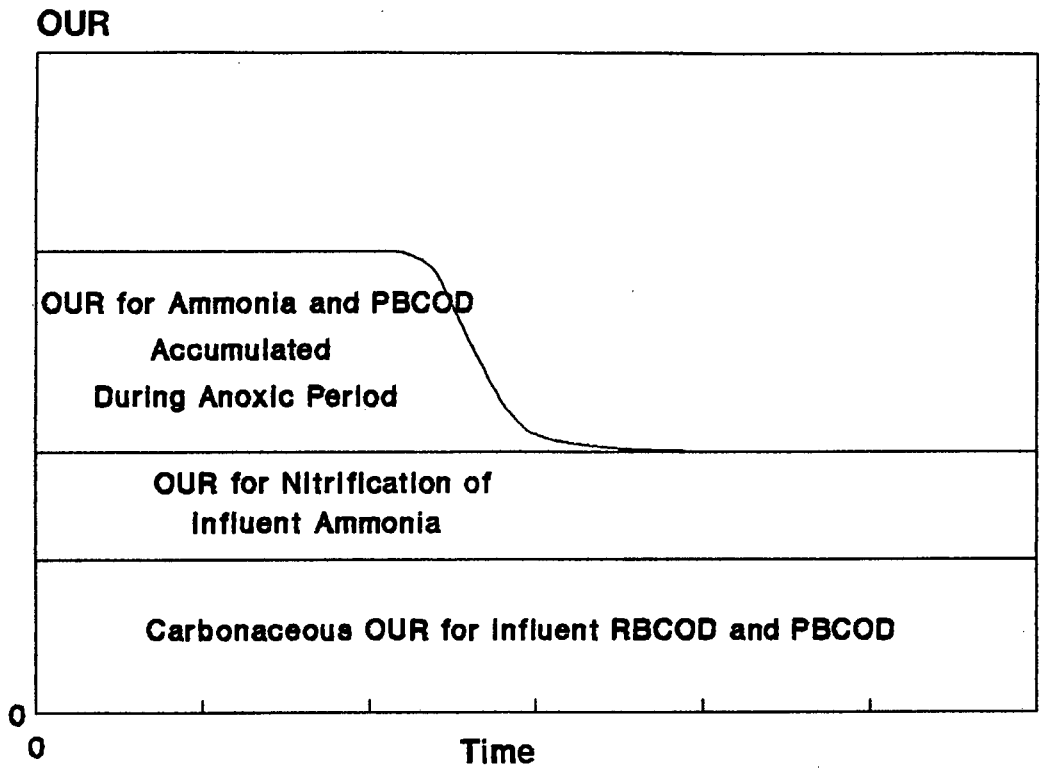



Fig 3.26: The changes observed in the OUR during the aerobic period of the intermittently aerated systems CFR 2 and CFR 3 when the aeration cycle was longer than 30 minutes (i.e. 8 hours,12hours, 24 hours and 72 hours). The changes observed were due to the consumption of ammonia and PBCOD accumulated during the anoxic period as shown on the graph.

sludge being exposed to low nitrate levels and partial anaerobism during this period. After 4 days, the duration of period 6, of too little nitrate dosing the nitrate dose was increased and marked the beginning of period 7 which lasted 21 days and during which an improved COD balance of 76% was obtained. Another possible contributory cause is that the sludge was adapting to the fully anoxic operating conditions. During period 6 the effluent was cloudy and sludge mass was being lost in the effluent. This was reflected by a reduction in MLSS (and MLVSS) in CFR 2 during this period (see Fig 3.22). The MLSS remained lower than with intermittent aeration for the remainder of the experiment. The second period of fully anoxic operation achieved a COD balance of 76% and this is in the same range as the COD balances achieved during phase 2 and the experimental procedure can be accepted as being reasonable for the purposes of this investigation.

**System Behaviour – Low F/M Filament Growth**

During phase 3 seven different aeration regimes were imposed on systems CFR 2 and CFR 3, the changes in the aeration cycles are briefly outlined in Table 3.13. The 7 aeration regimes/patterns are listed below, for each regime the frequency of exposure to aerobic anoxic conditions is given. The periods during which each system was exposed to the respective aeration regime is given and the changes in DSVI observed under each aeration regime are discussed with the respective aeration regimes.

(1) <u>15 to 30 minute aeration cycle</u>

The length of the aeration cycle was changed in order to maintain a 30% aerobic mass fraction. The frequency of exposure to aerobic anoxic conditions thus varied from 48 to 96 times per day. System CFR 2 was operated under this aeration pattern from startup to day 118 and system CFR 3 from startup to day 53. When the systems were exposed to the short aeration cycles a gradual increase in DSVI was observed. By day 53 the DSVI had increased from about 180 ml/g in both systems at startup to 244 ml/g and 251 ml/g for CFR 2 and CFR 3 respectively. On day 54 the sludge of both systems was combined and then split. This was to ensure the same DSVI and low F/M filament populations in the systems when the aeration regime of CFR 3 was changed to a longer cycle. After day 54 the DSVI in CFR 2 continued to increase and by day 118 the DSVI had increased to 400 ml/g. The increases in the DSVI's observed in both CFR 2 and CFR 3 when operated under the short aeration cycles was in agreement

Table 3.14: COD balance results calculated from daily measured data from systems CFR 2 and CFR 3 during phase 3. COD balances were calculated for those periods during which the aeration cycle was less than 30 minutes and for the periods during which the systems were operated under fully anoxic or continuously aerobic conditions.

| System | Period | Day to | Day | COD Balance % |
|---|---|---|---|---|
| Intermittent Aeration | | | | |
| CFR 2 | 1 | 0 | 53 | 83.6 |
| | 2 | 54 | 85 | 74.3 |
| | 3 | 86 | 117 | 69.2 |
| CFR 3 | 8 | 0 | 53 | 65.9 |
| Fully Aerobic | | | | |
| CFR 2 | 4 | 118 | 129 | 92.8 |
| | 5 | 182 | 192 | 96.7 |
| CFR 3 | 9 | 133 | 136 | 98.3 |
| | 10 | 158 | 166 | 86.9 |
| | 11 | 216 | 225 | 85.1 |
| | | | Average | 92 |
| Fully Anoxic | | | | |
| CFR 2 | 6 | 216 | 220 | 65.5 |
| | 7 | 221 | 242 | 76.4 |

with observations by Gabb *et al* (1989a) and Warburton *et al* (1991) on similar intermittently aerated single reactor systems operated on short aeration cycles.

(2) 12 hour aeration cycle

To maintain a 30% aerobic mass fraction the aeration cycle was 3.6 hours aerobic and 8.4 hours anoxic. The frequncy of exposure to anoxic/aerobic conditions was twice daily. The 12 hour aeration cycle was imposed on system CFR 3 from day 54 to 118. During this period the DSVI increased at a similar rate to that in system CFR 2 during the same period operated on short aeration cycles (see Fig 3.24).

(3) 24 hour aeration cycle

To maintain a 30% aerobic mass fraction the aeration cycle was 7.2 hours aerobic and 16.2 hours anoxic. The fequency of exposure to anoxic/aerobic conditions was once daily. System CFR 2 was exposed to a 24 hour cycle once from day 133 to 173 and system CFR 3 had this cycle imposed 3 times from day 119 to 132, day 137 to 157 and day 167 to 199. CFR 3 was exposed to this aeration regime three times because when settler failure occurred due to very high DSVI's the system was exposed to continuous aeration until the sludge settleability had improved to a manageable level whereupon the 24 hour cycle was reimposed. The 24 hour cycle was imposed on the systems at high and low DSVI values to observe if filament proliferation differed at different DSVI's. It was thought that when the sludge was exposed to a 24 hour aeration cycle the DSVI might reach a certain value, a plateau, for that regime but the DSVI increased apparently independently of the DSVI. The only difference in the low F/M filament growth observed was that when the 24 hour cycle was imposed on a system with a high DSVI (more than 300ml/g) then the DSVI increased much more quickly (CFR 3 from day 137 to 157) than if the same aeration regime was imposed at a lower DSVI (less than 200 ml/g) (CFR 2 from day 133 to 173).

(4) 72 hour aeration cycle (3 day cycle)

To maintain a 30% aerobic mass fraction the aeration cycle was 21.6 hours aerobic and 50.4 hours anoxic. Frequency of exposure to anoxic/aerobic conditions was once every three days or 0.33 per day. This long aeration cycle was imposed on both systems for relatively short periods, CFR 2 from

day 193 to 215 and CFR 3 from day 200 to 215. In CFR 2 the 72 hour cycle was imposed when the DSVI was about 135 ml/g and the DSVI increased fairly slowly at first and then increased more rapidly thereafter (see Fig 3.25 day 193 to 215). In CFR 3 the 72 hour cycle was imposed when the DSVI was about 320ml/g and the DSVI increased at a similar rapid rate to that observed with the 24 hour aeration cycle imposed just prior to the imposition of the 72 hour cycle. The operation of CFR 2 and CFR 3 with a 72 hour aeration cycle was terminated as there was no indication that this aeration regime was in any way ameliorating low F/M filament bulking.

(5) 8 hour aeration cycle (with no nitrate addition)

To maintain a 30% aerobic mass fraction the aeration cycle was 2.67 hours aerobic and 5.33 hours anoxic/anaerobic giving a frequency of exposure to aerated/unaerated conditions of 3 times per day. This aeration regime was imposed on system CFR 2 from day 173 to 181 and caused a rapid increase in DSVI from 268ml/g on day 173 to 404ml/g on day 181.

(6) Continuous aeration (100% aerobic mass fraction)

Nitrate addition was stopped when this aeration regime was instituted in systems CFR 2 and CFR 3. Continuous aeration was imposed on both systems a number of times during phase 3 to reduce excessive bulking when this occurred in the systems i.e. on CFR 2 between days 118 to 129 and 182 to 193 and on CFR 3 from days 133 to 136, 158 to 167 and 216 to 232. Continuous aeration was consistently effective in ameliorating low F/M filament bulking (see Figs 3.24 and 3.25).

(7) Fully anoxic conditions

When fully anoxic conditions were imposed on CFR 2 on day 216 the DSVI initially increased sharply. This was caused by a nitrate deficit and a decrease in the MLSS concentraion due to sludge debris being lost in the effluent causing a cloudy effluent. When the mass of nitrate dosed into the system was increased on day 221 the DSVI decreased slowly but nevertheless continued to decrease to about 100ml/g by day 241.

The filament growth during phase 3 is given in Figs 3.24 and 3.25. The changes observed in filament dominance were not specific to any of the different aeration cycles imposed on the systems but instead a gradual change was observed over most

of the experimental period during which the systems were exposed to intermittent aeration. The main change during this period (day 0 to 193) was the dominance of 021N in both systems for most of the period until day 102. After this *Microthrix parvicella* became dominant in both systems from day 133 to day 193.

At startup *Nocardia* sp. was dominant in CFR 2 with 0092 secondary and 0041, 021N and *H.hydrossis* present at a tertiary level. In CFR 3 021N was dominant, *Nocardia* sp. and 0092 both secondary and 0041, 1851 and *H.hydrossis* present at a tertiary level. By day 28 021N and 0092 were dominant in CFR 2 and CFR 3 respectively with 0092 secondary in CFR 2 and 021N and *Nocardia* sp. both secondary in CFR 3; also *M.parvicella* had appeared in both systems at a tertiary level. After this, in filament identifications on days 43, 75 and 102, type 021N was dominant in both systems with 0092 secondary in both on day 43. By day 75 *M.parvicella* had increased to the secondary level in both systems and on day 102 it was still present in both systems at this level. On day 75 0092 was also present at the secondary level in CFR 2 and on day 102 0092 was secondary with *M.parvicella* in CFR 3.

By day 133 *M.parvicella* had become dominant in both systems (see Fig 3.25) and remained dominant in both until day 193 just prior to the imposition of the 72 hour aeration cycles. The secondary filaments during this period changed considerably. In CFR 2 on day 133 type 0041 was secondary whereas 021N was secondary in CFR 3. On day 160 021N was secondary in both systems . By day 193 021N had disappeared completely from both systems and 0961 and 0092 were secondary in CFR 2 and CFR 3 respectively. On day 216 after the systems had been exposed to the 72 hour aeration cycles type 0803 was dominant in CFR 2 with 0092 secondary. *M.parvicella* had decreased to a tertiary level along with 021N, *Thiothrix* sp. and 0961. In CFR 3 on day 216 *M.parvicella* was still dominant, types 0092 and 1701 both secondary and *Thiothrix* sp. and 0041 both present at a tertiary level.

By day 241 after the fully anoxic operation of CFR 2 type 0803 had disappeared from the system and 0092 had become dominant with *M.parvicella* secondary. 021N and 0041 were present at a tertiary level on this day.

The progression of *M.parvicella* from being absent at startup to dominance in both systems showed that this filament's ability to dominate in intermittent aeration continuously fed single completely mixed reactor systems receiving real sewage as

feed, as observed previously by Warburton *et al* (1991) in short aeration cycle systems, was unaffected by the frequency of exposure to aerobic/anoxic conditions (i.e. changes in the length of the aeraton cycle) while the aerobic mass fraction remained at 30%. The growth of *M.parvicella* was very different in the 2 systems when exposed to the 72 hour aeration cycles with the filament decreasing to a tertiary level in CFR 2 whereas it maintained its dominant status in CFR 3. The reason for this difference in behaviour could not be explained.

The ineffectiveness of reducing the frequency of alternation between aerobic and anoxic conditions in controlling the growth of low F/M filaments in intermittently aerated continuously fed single completely mixed reactor systems shows that this would not be a viable method of bulking control in intermittent aeration systems. It also explains why low F/M filaments also proliferate in multi reactor N and N & P removal systems wherein the frequency of alternation between anoxic and aerobic conditions is much lower than in intermittent aeration systems i.e. usually between 1 and 5 times daily. The operation of the two systems under fully aerobic and anoxic conditions at the end of this phase demonstrates again that continuous aeration and fully anoxic conditions ameliorate low F/M filament bulking. From the strong positive ameliorating effect of fully anoxic and aerobic conditions it is possible that using very low frequencies of alternation, eg. 1 every 10 days, low F/M filament bulking may be alleviated but such low values are impractical to implement.

### 3.4.3 Conclusions for phase 3

(1) Decreasing the frequency of alternation between anoxic and aerobic conditions from 48 times/d to once every 3 days in intermittently aerated continuously fed single completely mixed reactor systems receiving real sewage as feed at an aerobic mass fraction of 30% does not ameliorate low F/M filament bulking. The persistence of low F/M filament bulking even at low frequnecies of alternation is consistent with the observation of bulking in multi reactor N and N & P removal systems wherein frequencies of alternation are low, usually around 1 to 5 times daily.

(2) Fully anoxic and fully aerobic conditions in continuously fed completely mixed single reactor systems with bulking caused by low F/M filaments ameliorated the bulking in all cases with fully aerobic conditions leading to more rapid reductions in the DSVI than fully anoxic conditions.

# CHAPTER 4

## CONCLUSIONS

Filamentous bulking causes considerable settling problems in full scale nitrogen (N) and nutrient (N & P) removal activated sludge plants in South Africa. In two surveys in 1985 and 1987 Blackbeard *et al* (1986, 1988) found that the majority of bulking problems were caused by filaments in the low F/M (or long sludge age) group of organisms (classification according to Jenkins *et al*, 1984). From the findings of Blackbeard *et al* (1986, 1988) an extensive research project was undertaken by Gabb *et al* (1989a) into specific control of low F/M filament bulking. This project investigated the effectiveness of selectors, the proposed method of low F/M filamentous bulking control and found them to be ineffective.

In order to obtain a better understanding of the causes and control of low F/M filament bulking a second comprehensive laboratory research investigation was commenced in 1989. The work presented in this thesis forms a part of this investigation and evaluated the effect of fully anoxic conditions and the frequncy of alternation between anoxic and aerobic conditions on low F/M filament bulking. The experimental investigation was conducted in 3 phases investigating

(1) the effect of fully anoxic conditions and low nitrate concentrations during the anoxic phase of an intermittent aeration cycle on low F/M filament growth in continuously fed completely mixed single reactor systems receiving a synthetic sewage feed

(2) the effect of fully anoxic conditions on low F/M filament growth in continuously fed completely mixed single reactor systems receiving real sewage

(3) the effect of alternating the frequency of exposure of low F/M filaments to anoxic/aerobic conditions (i.e. increasing the length of the aeration cycle but maintaining the aerobic mass fraction) in intermittently aerated continuously fed single completely mixed reactor systems.

In phase 1 two continuously fed single completely mixed reactor systems were operated: system CFR 1 was a control intermittently aerated system operated with short aeration cycles (up to 30 minutes per cycle with a dissolved oxygen (DO)

concentration up to 3.0mgO/l) and system ANOX 1 was a fully anoxic system. Both systems were fed a synthetic sewage previously shown by Gabb *et al* (1989a)( (but not reported by them) and Casey *et al* (1990) to support the proliferation of some low F/M filaments, and which contained RBCOD and PBCOD in the same proportion as found in real domestic sewage.

In CFR 1 when no nitrate was dosed to the system, to induce low nitrate concentrations in the anoxic period of the aeration cycle, the DSVI decreased to below 80ml/g and operational problems were encountered with the sludge clogging the overflow tube and the settler of the system. The clogging problems were the result of the production of polymeric material by the sludge which caused the coagulation of the sludge flocs into large clumps. The reason for the production of the polymeric material is unknown. When nitrate was dosed to ensure sufficient nitrate in the system during the anoxic period the sludge quality did not improve even after seeding with a low F/M filament bulking sludge in order to increase the DSVI and improve the sludge quality. Despite the poor sludge quality, the sludge settleability was good and the DSVI remained below 100ml/g. From this it was concluded that in intermittently aerated single reactor systems receiving the synthetic sewage as feed, low nitrate concentrations during the anoxic period lead to amelioration of low F/M filament bulking caused by the filaments 1851 and 1701, which were dominant and secondary respectively at startup, and low DSVI values. It is possible that the unexplained production of polymeric material could have played a role in the reduction of the DSVI.

In the fully anoxic system ANOX 1 an initial decrease in DSVI from about 250ml/g to 130ml/g by day 24 was caused by the decline of filament type 1701 from dominance along with the decline of all other low F/M filaments except for *H.hydrossis.* This filament became dominant and after the initial decline in DSVI caused an increase in DSVI to above 200ml/g for the remainder of the phase 1 period. For the duration of operation of ANOX 1, low F/M filaments like 0092, 0041, 0803 and 0961 either disappeared from the system or were present at a tertiary level but were unable to proliferate under the fully anoxic conditions and did not contribute to bulking. Only *H.hydrossis* was able to proliferate excessively and cause bulking under the fully anoxic operating conditions. At one stage during phase 1 ANOX 1 was operated partially anaerobic for a 10 day period when nitrate dosing to the system was decreased. This led to explosive proliferation of *H.hydrossis* and a dramatic increase in the DSVI to 400ml/g. When anoxic conditions were

reestablished the DSVI decreased to a comparatively low value but remained above 200ml/g and showed eratic changes for the remaining 65 days of the experimental period.

From phase 1 it was concluded that in ANOX 1, the fully anoxic system fed synthetic sewage, only *H.hydrossis* was able to proliferate to the extent of causing bulking; other low F/M filaments were able to grow in the system but not to the extent of causing bulking. As *H.hydrossis* is a filament of little consequence in low F/M bulking in systems fed real sewage, but proliferated in laboratory systems fed the developed synthetic sewage it was decided to report the phase 1 experiments but feed the fully anoxic system with real domestic sewage instead of the synthetic sewage to examine the effect of fully anoxic conditions on the low F/M filaments other than *H.hydrossis*.

During phase 2 of the investigation two fully anoxic continuously fed single completely mixed reactor systems, ANOX 2 and ANOX 3, both identical to ANOX 1, were operated receiving real raw sewage as feed. Sufficient nitrate was dosed to the systems to ensure anoxic conditions. The DSVI of both systems, which were started up with totally different low F/M filament populations, (i.e. ANOX 2 had *H.hydrossis* dominant and 1851 secondary, and ANOX 3 had 0092 dominant and 021N secondary) showed a rapid decrease from 250ml/g and 180ml/g for ANOX 2 and 3 respectively to less than 100ml/g by day 20 and decreased to less than 80ml/g even though the filament abundance in both systems was still at the common to very common level. It was concluded from these observations that low F/M filaments were unable to proliferate to the extent of causing bulking in fully anoxic continuously fed single completely mixed reactor systems fed real sewage. In addition to this it was concluded that the excessive growth of *H.hydrossis* under fully anoxic conditions observed in ANOX 1 during phase 1 was attributable to the synthetic sewage feed and was not a true reflection of that filament's growth under the same conditions when fed real sewage.

Because fully anoxic conditions did not support excessive low F/M filamentous growth and neither did continuous aeration (observed previously by Gabb *et al*, 1989a) it was proposed that if the low F/M filaments were exposed to long periods of anoxic and aerobic conditions thereby decreasing the frequency of exposure to alternating anoxic and aerobic conditions, then the filaments may behave similarly to that observed in the respective fully anoxic or aerobic conditions and bulking may be

ameliorated. Accordingly phase 3 of the investigation was initiated using intermittently aerated systems but reducing progressively the frequency of alternation between anoxic and aerobic conditions.

In phase 3 two intermittently aerated continuously fed single completely mixed reactor systems, CFR 2 and CFR 3, were operated receiving real sewage feed. A 30% aerobic mass fraction was maintained throughout this phase and was selected because it was found that this best promoted low F/M filament proliferation. The length of the aeration cycle was varied from 30 minutes per cycle (48 cycles/d) to 72 hours per cycle (1 cycle every 3 days) with intermediate cycle lengths of 8 hours, 12 hours and 24 hours.

All the intermittent aeration cycles imposed on CFR 2 and CFR 3 caused low F/M filament proliferation with the DSVI increasing in all cases to over 400ml/g whether the aeration cycle was imposed on the system at a low (less than 150ml/g) or a high (greater than 200ml/g) DSVI. When the DSVI increased to an unmanagable level, usually around 400ml/g, causing settler failure the systems were continuously aerated to reduce the DSVI before imposing an intermittent aeration regime again. If the DSVI in the system was less than 150ml/g when the intermittent aeration cycle was imposed on the system then the increase in DSVI was slower than if the same aeration regime was imposed on a system at a higher DSVI.

The filament growth during phase 3 showed gradual changes over long periods of time with none of the changes observed being directly attributable to a particular aeration pattern. From startup type 021N became dominant in both systems and remained dominant until day 102. By day 43 *Microthrix parvicella* had appeared in the systems and increased in status until it became dominant in both systems by day 133, remaining dominant in both CFR 2 and CFR 3 until day 190, just prior to imposing the 72 hour aeration cycles on the systems. On day 216, when the 72 hour aeration cycles were ended type 0803 had become dominant in CFR 2 and *M.parvicella* was still dominant in CFR 3 giving no clear indication of which filaments favour this aeration regime. From phase 3 it was concluded that frequency of alternation of anoxic/aerobic conditions in intermittently aerated continuously fed single completely mixed reactor systems had no effect in reducing bulking caused by low F/M filaments in these systems.

At the end of the phase 3 experimental period one system (CFR 3) was switched to continuous aeration and the other (CFR 2) to fully anoxic operation and both of these operational regimes led to amelioration of the low F/M filament bulking in the systems. On day 241 after exposure to fully anoxic conditions 0092 was dominant in CFR 2 showing that this filament could grow better than other low F/M filaments such as *M.parvicella* under these conditions but not to the extent of causing bulking. These findings confirmed the earlier observations that fully anoxic and fully aerobic operation of single reactor systems led to amelioration of the low F/M filament bulking with continuous aeration leading to more rapid decreases in DSVI than fully anoxic operation.

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## APPENDIX A

### Constituents and Makeup of the Synthetic Sewage

The Synthetic Sewage was made up using the following 7 suspensions:

| Vitamins | g/5ℓ |
|---|---|
| Pantothenic Acid | 1.400 |
| Nicotinic Acid | 1.400 |
| D–Biotin | 0.07 |
| Cyanocobalamin | 0.07 |
| Folic Acid | 0.07 |
| Pyridoxine | 1.400 |
| Cocarboxylase | 1.400 |
| 4,aminobenzoic Acid | 1.400 |
| Inositol meso | 1.400 |
| Thiaminium Dichloride | 1.400 |
| Riboflavin | 1.400 |
| Choline Chloride | 1.400 |

| Readily Biodegradable COD ($S_{bsi}$) | g/5ℓ |
|---|---|
| Lactose | 3.3 |
| Acetate | 13.8 |
| Succinate | 8.7 |
| Citrate | 26.4 |
| D–Glucose | 3.3 |
| Maltose | 3.3 |
| Glycerol | 5.4 |
| Lactic Acid | 20.0mℓ |
| Ethanol | 9.0mℓ |
| Butanol | 4.5mℓ |

| Micro Inorganic Nutrients | g/5ℓ |
|---|---|
| $FeSO_4.7H_2O$ | 8.62 |
| $ZnSO_4.7H_2O$ | 2.46 |
| $MnSO_4.4H_2O$ | 2.46 |
| $CuSO_4.5H_2O$ | 0.50 |
| $CoCl_2.6H_2O$ | 0.52 |
| $Na_2MoO_4.2H_2O$ | 0.25 |
| $H_3BO_3$ | 0.50 |
| KI | 0.12 |

| Additional Micronutrients | g/5ℓ |
|---|---|
| $NiCl_2.6H_2O$ | 0.250 |
| $AlCl_3.6H_2O$ | 0.100 |
| $NH_4VO_3$ | 0.025 |
| $Na_2SeO_3$ | 0.010 |
| $TiO_2$ | 0.040 |
| $Na_2WO_4.2H_2O$ | 0.015 |

| Organic Nitrogen | g/8ℓ |
|---|---|
| Casein | 10.80 |
| Peptone | 20.20 |
| Yeast Extract | 20.20 |
| Gelatin | 15.80 |

| Macro Inorganic Nutrients | g/15ℓ |
|---|---|
| $NH_4Cl$ | 162.0 |
| $K_2HPO_4$ | 57.0 |
| $KH_2PO_4$ | 3.0 |
| $MgCl_2.6H_2O$ | 198.0 |
| $CaCl_2.2H_2O$ | 49.5 |

| Complex Carbohydrates | g/15ℓ |
|---|---|
| Starch | 50.55 |
| Cellulose | 39.60 |
| Agar | 7.95 |
| Dextrin | 69.15 |

| Preparation of Feed(for each system) | mℓ/10ℓ |
|---|---|
| Vitamins | 30mℓ |
| Micro Inorganic Nutrients | 30mℓ |
| $S_{bsi}$ | 30mℓ |
| Additional Micronutrients | 50mℓ |
| Organic Nitrogen | 140mℓ |
| Macro Inorganic Nutrients | 170mℓ |
| Complex Carbohydrates | 350mℓ |

Note : Ensure that all the suspensions are well mixed prior to making up the feed.

# APPENDIX B

## EQUIPMENT USED AND PROCEDURE FOLLOWED FOR THE ANOXIC AND AEROBIC BATCH TESTS PERFORMED DURING PHASE 2

### B.1 Equipment Used for Batch Test Experiments

All the batch tests, on days 19 and 43, were carried out in sealed single completely mixed reactors. The reactor had a diameter of 120mm and the volume was 3$\ell$. The inlet and outlet ports of the reactors were sealed off and the contents were poured into the reactor vessel through the access port in the reactor cover just prior to the start of the batch test.

### B.2 Anoxic Batch Tests (day 43)

The anoxic batch tests were designed to measure the denitrification rates in the sludge from continuously anoxic systems to enable comparison with values measured in nutrient removal systems. At the start of the anoxic batch tests, 2$\ell$ volumes of sludge harvested from the appropriate system was transferred to the batch reactor as quickly as possible. Since anoxic conditions were essential for the tests, the first step was to de–oxygenate the sludge (small amounts of air were introduced into the sludge during the transfer of the sludge from the parent system to the batch test reactor) and this was done by bubbling nitrogen gas through the batch vessel for about 20 minutes while the contents were being gently stirred continuously. The DO was monitored with a Yellow Springs Instrument Co. DO probe attached to a DO meter until it reached zero. It was important that the probe was accurately calibrated because even very low values of DO can inhibit denitrification.

Also important for the batch test was that sufficient nitrate was present in the reactor for the denitrification rates to be measured. In previous anoxic tests Clayton *et al* (1990) had found that a starting nitrate concentration of about 20mgN/l was enough to measure the denitrification rates. It was found that the nitrate present in sludge taken from systems ANOX 2 and ANOX 3 gave an initial nitrate concentration of about 25mgN/l in the batch reactor and therefore no additional nitrate was added to the sludge in the batch reactor prior to the start of the batch tests.

Once the DO was reduced to zero 1$\ell$ of raw sewage was added to the reactor and

sampling was commenced immediately. Samples were pipetted out of the batch reactor and immediately filtered through Whatman's No.1 paper after which two drops of 8.6g/$\ell$ $HgCl_2$ were added to kill any remaining bacterial cells in the sample. Samples were stored overnight and analysed the next day for $NO_3$–N. During the test mixed liquor samples were taken for MLVSS analysis. Samples were taken every 5 minutes for the first 30 minutes, every 10 minutes for the next 30 minutes, then every 20 minutes for the next 2 hours and finally every 30 minutes for the last hour of the test (total test time was 4 hours in both cases).

Throughout the tests precautions were taken to ensure that no oxygen was dissolved into the mixed liquor. For this purpose a stream of nitrogen gas was bubbled through the batch reactor for the duration of the test period. This not only purged the mixed liquor of dissolved oxygen but also formed an inert layer of gas between the mixed liquor surface and the air above preventing further oxygen dissolution. Small plastic spheres (about 15mm in diameter) were also floated on the surface of the reactor contents to further isolate the mixed liquor from the atmosphere. The pH of the mixed liquor was maintained between 7.4 and 7.8 (the usual operating limits of activated sludge systems) throughout the experiments by adding small amounts of 20% hydrochloric acid to the reactor contents. This was necessary because denitrification is a process producing alkalinity and the pH of the mixed liquor tended to rise throughout the experiment.

From the nitrate concentrations measured in the samples, nitrate concentration – time curves were plotted (see Fig 3.16 in chap 3) for each batch test. From these curves the denitrification rates and thus also the rates of RBCOD and PBCOD utilisation under anoxic conditions were calculated. The denitrification rate constants were calculated using the method developed by Ekama and Marais (WRC, 1984). The construction developed by them and applied to the nitrate concentration curves is given in Fig B.1.

## B.3 Aerobic Batch Tests (day 19 & 43)

The aerobic batch tests were designed to evaluate the response of the activated sludge fed real raw sewage to aerobic conditions after continuous exposure to anoxic conditions in ANOX 2 and ANOX 3. It was thought that the rate of aerobic metabolism of the sludge might have diminished or even been lost after extended

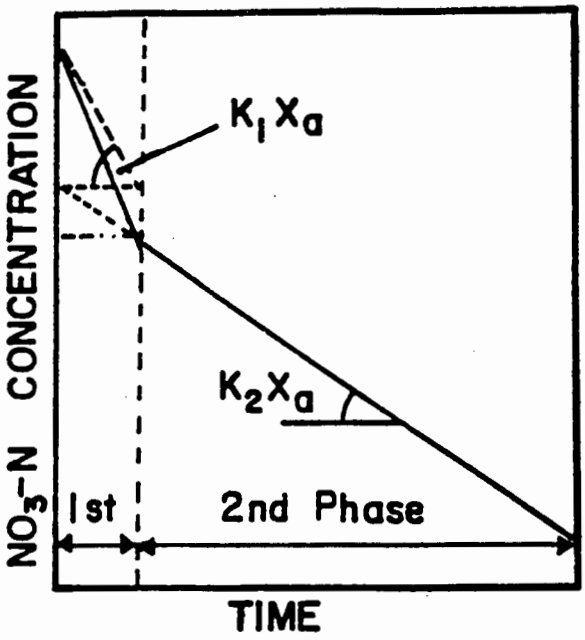


Fig B.1: The construction developed by Stern and Marais (1974) (from WRC, 1984) for the calculation of the denitrification rate constants $K_1$ and $K_2$ from nitrate concentration – time curves plotted from data obtained during anoxic batch tests. In the first phase both rates are active giving a utilisation rate of $K_1 + K_2$. In the second phase only $K_2$ is active and therefore by extrapolating $K_2$ to the x-axis the 2 rates can be separated and calculated separately.

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exposure to continuous anoxic conditions.

The batch test reactors were the identical ones used for the anoxic batch tests except that now they were aerated by attaching a low pressure airline to an airstone in the base of the reactors. The air flow rate was regulated by a fine needle valve. Aeration was controlled by a solenoid switch attached to a DO meter which controlled the DO concentration between lower and upper DO set points 2 and 4mgO/l throughout the test and automatically measured the OUR between the upper and lower set points during the air off period as the DO decreased due to consumption of oxygen by the sludge (Randall *et al*, 1991).

The aerobic batch tests were also started with 2$\ell$ volumes of sludge being placed in the batch test reactors although the tests on day 19 and 43 differed slightly. The

batch test on day 19 was performed on 2$\ell$ of combined sludge (1$\ell$ from each of ANOX 2 and ANOX 3) placed in a batch reactor. In this test nitrification was not inhibited because the nitrifying organisms, obligate aerobes, were expected to have died out in the sludge due to the extended exposure of the sludge to anoxic conditions in the systems. On day 43 batch tests were performed on sludge taken from each of ANOX 2 and ANOX 3. These aerobic tests were performed on the same sludge that was used in the anoxic batch tests described above. In these tests nitrification was inhibited by the addition of thiourea even though none was expected as mentioned above. After completion of the anoxic batch tests the stirrer in both of the batch test reactors was switched off and the sludge allowed to settle. Some of the supernatant was then drawn off and more sludge added from the parent systems to increase the MLVSS to make up for the sludge that was removed from the reactors for sampling during the anoxic batch tests. After supplementing the sludge mass in the reactor gentle stirring and aeration was again commenced and both continued for the duration of the batch test. After about 2 hours aeration 1$\ell$ of real raw sewage was added.

The OUR was measured from the time the aeration was started to the end of the tests 24 hours later. After the sewage was added to the reactors 50m$\ell$ samples were pipetted from the systems every 10 minutes for 3 hours. The samples were treated the same way as in the anoxic batch tests above but were analysed for soluble COD (<0.45$\mu$m) concentration. Nitrate and TKN concentrations were not analysed because nitrification was absent.

In all the aerobic batch tests mixed liquor samples were taken for MLVSS analysis. The OUR profiles [mgO/(l.h)] obtained from the OUR meter were divided by the estimated active organism concentration and plotted in Figs 3.17 and 3.18 (see chap 3) as specific OUR mgO/(gAVSS.h). The RBCOD utilisation rate under aerobic conditions was then be calculated from this data using the method of Ekama *et al* (1986).

## B.4 Estimation of the Active Fraction (fav) of the MLVSS

For the calculation of the active organism specific denitrification rates (and RBCOD and PBCOD utilisation rates under anoxic conditions) and aerobic RBCOD and PBCOD rates, it is necessary to estimate $f_{av}$ to calculate the mass of active VSS present in the batch test reactors from the measured MLVSS concentration. Using

the steady state theory (WRC, 1984) and applying it to the experimental data measured for phase 2 an average $f_{av}$ of 0.42 was calculated. Due to uncertainty regarding the accuracy of kinetic constants such as the biological yield coefficient, $Y_h$, and the endogenous respiration coefficient, $b_h$, under continuous anoxic conditions it was uncertain how accurate this $f_{av}$ value was and therefore for the purposes of this investigation a $f_{av}$ of 0.40 was accepted.

## APPENDIX C

**Procedure for the calculation of the Kinetic Variables for the Data measured from ANOX 2 and ANOX 3 during phase 2.**

The procedures for the calculation of the kinetic behaviour evaluation are set out below:

1. The amount of nitrate denitrified gives an equivalent carbonaceous oxygen utilisation rate (OUR) under anoxic conditions that is the sum of the equivalent OUR for the utilization of RBCOD (i.e. RBCODOUR) and PBCOD (i.e. PBCODOUR). Because the fully anoxic systems ANOX 2 and 3 were continuously fed, the specific RBCOD loading rate [RBCODLR, mgRBCOD/mgAVSS.h)] onto the active VSS under anoxic conditions can be calculated and is given by :

$$RBCODLR_{anx} = \frac{f_{bs}.M(S_{bi}).\text{anoxic fraction}}{24.\text{anoxic fraction}.MX_a} \qquad \text{(mgCOD/(mgAVSS.h)}$$

$$= \frac{f_{bs}.M(S_{bi})}{24 . MX_a}$$

where

$f_{bs}$ = readily biodegradable COD fraction of the influent COD with respect to the biodegradable COD concentration

$M(S_{bi})$ = mass of biodegradable COD in the influent – $M(S_{bi}) = M(S_{ti}).(1-f_{up}-f_{us})$

$M(S_{ti})$ = mass of influent COD

$f_{up}$ = unbiodegradable particulate fraction of $S_{ti}$

$f_{us}$ = unbiodegradable soluble fraction of $S_{ti}$

$MX_a$ = volatile active mass in the system

where

$MX_a = f_{av}.MX_v$

where

$MX_v$ = mass of VSS in reactor

$= X_v V_p$

$X_v$ - - - = measured VSS concentration (mgVSS/ℓ)
$V_p$ = volume of the reactor (ℓ)
$f_{av}$ = active fraction of the VSS.

The active fraction of the VSS, $f_{av}$, is calculated via the steady state activated sludge theory of Marais and Ekama (1976) (see also WRC, 1984) as follows:

(1) First the value of $f_{up}$ i.e. the unbiodegradable particulate fraction of the influent COD is calculated;

In the steady state activated sludge theory

$$MX_v = M(S_{ti}) \left[ \frac{Y_h.R_s.(1-f_{us}-f_{up})}{(1+b_h.R_s)} (1+f.b_h.R_s) + \frac{f_{up}.R_s}{f_{cv}} \right] \qquad (C.1)$$

where
$Y_h$ = yield coefficient
= 0,45 mgVSS/mgCOD
$R_s$ = sludge age (d)
$b_h$ = endogenous respiration rate
= 0,24/d at 20° C
f =unbiodegradable fraction of the active VSS (endogenous residue)
= 0,20
$f_{cv}$ = COD/VSS ratio of the sludge
= 1,48 mgCOD/mgVSS

The $f_{up}$ is found by substituting the known values of the kinetic parameters ($Y_h$,$f_{cv}$,$b_h$ and f) and the measured values for $MX_v$, $M(S_{ti})$ and $R_s$ into Eq (C.1) leaving only $f_{us}$ and $f_{up}$ undefined. From occasional measuremnets of the filtered effluent COD concentration the unbiodegradable soluble COD fraction, $f_{us}$, was estimated to be 0.1 mgCOD/mgCOD from the ratio of the measured filtered effluent COD concentration divided by the total influent concentration (i.e. $f_{us} = S_{ue}/S_{ti}$, see WRC, 1984). Knowing $f_{us}$ leaves $f_{up}$ the only remaining unknown parameter; It therefore can be calculated by solving Eq (C.1), with average experimentally measured values for $MX_v$, $MS_{ti}$ and $R_s$ for each steady state period.

(2) Knowing $f_{up}$, the active mass $MX_a$ and active fraction of the VSS, $f_{av}$, viz. $MX_a/MX_v$ can be calculated as follows:

$$MX_a = M(S_{ti}).(1-f_{us}-f_{up})Y_h.R_s/(1+b_h.R_s)$$

Then the active fraction is given by

$$f_{av} = MX_a/MX_v$$

where $MX_v$ is the experimentally measured value.

Now for continuously fed completely mixed systems i.e. ones wherein a selector effect is not induced, the RBCODUR under anoxic and aerobic conditions have been measured (see Gabb et al., 1989a) and were found to be approximately the same under anoxic and aerobic conditions and in the range 50–150 mgRBCOD/(gAVSS.h) [which corresponds to a maximum specific growth rate of 0,7–2,1 mgAVSS/(mgAVSS.d)]. The RBCODUR on the two anoxic systems operated in this investigation was always much lower [i.e. 5,68 mgRBCOD/(gAVSS.h), see Table 3.9] than the utilization rate cited above. From this it was accepted that the RBCOD would be utilized as fast as it was loaded onto the fully anoxic systems i.e. RBCODUR = RBCODLR where RBCODLR is the RBCOD loading rate onto the system [mgRBCOD/(mgAVSS.h)]. Accepting this, it was possible to calculate the PBCOD utilization rate under anoxic conditions by deducting the RBCODUR from the measured total COD (PBCOD + RBCOD) utilization rate where the total rate was calculated from the measured nitrate reduction rate under anoxic conditions.

2. Thus the PBCOD utilization rate (PBCODUR, mgPBCOD/mgAVSS.h) under anoxic conditions is given by:

$$PBCODUR_{anx} = \left[\frac{2,86.M(N_{nd}).(1-f_{cv}.Y_h)}{24.\text{anoxic fraction}.MX_a}\right] - RBCODUR$$

(mgCOD/gAVSS.h)

where

| | |
|---|---|
| 2,86 | = oxygen equivalent of nitrate($mgO/mgNO_3$-N) |
| $MN_{nd}$ | = mass of nitrate denitrified (mgN/d) |
| $(1-f_{cv}.Y_h)$ | = 0,33 mgO consumed/mgCOD utilized. |
| $V_p$ | = reactor volume ($\ell$) |

For each of the 6 steady state periods the abovementioned COD utilization rates were calculated and are tabulated in Table 3.9 (see Chapter 3).

# APPENDIX D

Experimental Data measured on systems CFR 1 and ANOX 1 during phase 1 of the investigation.

Month; May 1989

| Day | | | | CFR 1 | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Influent | | | | | | | | | | Effluents | | | | Infl. |
| | Date | COD | TKN | MLSS | VSS | DSVI | Sett | pH | OUR | peak | Aerob | COD | TKN | NO3 | | NO3 |
| | | mg/l | mg/l | mg/l | mg/l | ml/g | ml/l | | | | % | mg/l | mg/l | mg/l | | |
| | 1 | | | | | | | | | | | | | | | |
| | 2 | | | | | | | | | | | | | | | |
| | 3 | | | | | | | | | | | | | | | |
| | 4 | | | 1828 | | 197 | 360 | 7.5 | 22.5 | | | | | 4 | | |
| | 5 | | | | | | | | | | | | | | | |
| | 6 | 558 | 60.5 | | | | | | | | | 137 | 23.8 | 1.48 | | |
| | 7 | | | | | | | | | | | 165 | 27.4 | 12.06 | | |
| | 8 | 564 | 61 | | | | | | | | | | | | | |
| | 9 | | | | | | | | | | | | | | | |
| 1 | 10 | | | | | | 580 | | | | | 133 | 21.8 | 1.97 | | |
| 2 | 11 | 548 | 57.7 | | | | 520 | 7.5 | | | | 125 | | 2.6 | | |
| 3 | 12 | 415 | | 2592 | 2308 | 193 | 500 | 7.54 | | | | 79 | | 4.51 | | |
| 4 | 13 | 552 | | | | | | | | | | 121 | 17.9 | 5.21 | | |
| 5 | 14 | 500 | 65.5 | 2784 | 2518 | 180 | 500 | 7.52 | 16.6 | 3.2 | | 89 | 11.8 | 3.67 | | |
| 6 | 15 | 519 | 63 | 2776 | 2464 | 195 | 540 | 7.62 | 13.5 | 3.2 | | 97 | 13.4 | 1.86 | | |
| 7 | 16 | 519 | 63.8 | 2526 | 2186 | 219 | 552 | 7.56 | 37.6 | 2.1 | 21 | 130 | 16.2 | 2.11 | | |
| 8 | 17 | 552 | 62.2 | 2414 | 2164 | 232 | 560 | 7.61 | 35 | 2.2 | 32.2 | 101 | 19.3 | 2.51 | | |
| 9 | 18 | 491 | 61.6 | 2416 | 2190 | 232 | 560 | 7.54 | | | | 95 | 17.1 | 2.55 | | |
| 10 | 19 | 535 | 63.3 | 2998 | 2712 | 200 | 600 | 7.4 | | | | 105 | 17.1 | 2.5 | | |
| 11 | 20 | 527 | 69.7 | 2856 | 2300 | 189 | 540 | 7.39 | 32.2 | 2.34 | 38.6 | 82 | 6.7 | 6 | | |
| 12 | 21 | 794 | 99 | 2440 | 2118 | 213 | 520 | 7.5 | 33.6 | 2.2 | 26 | 78 | 12.7 | 5.12 | | |
| 13 | 22 | | | 2894 | 2606 | 186 | 540 | 7.64 | 35.1 | 2.4 | 32.4 | 90 | 7.8 | 7.57 | | |
| 14 | 23 | 632 | 59.6 | 1936 | 1648 | 207 | 400 | 7.6 | 24 | 2.4 | 41.8 | 82 | 7.6 | 7.5 | | |
| 15 | 24 | 661 | 59 | 2218 | 1954 | 216 | 480 | 7.39 | 32 | 2.6 | 37 | 66 | 7.6 | 12.4 | | |
| 16 | 25 | 566 | 57.1 | 2724 | 2474 | 191 | 520 | 7.47 | 41 | 2.4 | 29 | 64 | 7.8 | 8 | | |
| 17 | 26 | 472 | 64.7 | 2570 | 2322 | 187 | 480 | 7.54 | 37 | 2 | 29 | 66 | 12.3 | 3 | | |
| 18 | 27 | 570 | 61.6 | | | | | | | | | 70 | 10.6 | 4.9 | | |
| 19 | 28 | 554 | 60 | 2406 | 2154 | 200 | 480 | 7.59 | 33 | 2.3 | 30 | 86 | 15.1 | 10 | | |
| 20 | 29 | 513 | 57.4 | 2224 | 1936 | 216 | 480 | 7.6 | 35.8 | 2.3 | 31.8 | 73 | 9.5 | 10.3 | | |
| 21 | 30 | 533 | 58.2 | 2822 | 2476 | 170 | 480 | 7.59 | 38.8 | 2.3 | 29.1 | 94 | 7.6 | 10 | | |
| 22 | 31 | 546 | 60.5 | 1918 | 1660 | 219 | 420 | 7.57 | 30.8 | 2.5 | 35.8 | 98 | 9 | 7.6 | | |

Month; June 1989

| | | Influent | | CFR 1 | | | | | | | | Effluents | | | Infl. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Day | Date | COD mg/l | TKN mg/l | MLSS mg/l | VSS mg/l | DSVI ml/g | Sett ml/l | pH | OUR | peak | Aerob % | COD mg/l | TKN mg/l | NO3 mg/l | NO3 |
| 23 | 1 | 643 | 60.2 | 2740 | 2540 | 168 | 460 | 7.6 | 35.6 | 2.3 | 31 | 81 | 6.7 | 7.6 | |
| 24 | 2 | 652 | 57.7 | 2378 | 2102 | 202 | 480 | 7.6 | 34.2 | 2.2 | 30.6 | 76 | 7.6 | 8 | |
| 25 | 3 | 491 | 57.7 | | | | | | | | | 80 | 6.7 | 9.8 | |
| 26 | 4 | 516 | 56.3 | | | | | 7.5 | 30.3 | 2.5 | 37 | 97 | 6.2 | 12.2 | |
| 27 | 5 | 639 | 58.5 | 1782 | 1636 | 191 | 340 | 7.57 | 32.1 | 2.4 | 42.4 | 97 | 7 | 15.7 | |
| 28 | 6 | 594 | 59.1 | 1748 | 1406 | 183 | 320 | 7.72 | 27.6 | 2.3 | 37.6 | 121 | 13.2 | 14 | |
| 29 | 7 | 604 | 57.1 | | | | | 7.6 | 25.7 | 2.4 | 42.9 | 100 | 7.6 | 11.8 | |
| 30 | 8 | 539 | 48.7 | 1640 | 1426 | 171 | 280 | 7.57 | 29.1 | 2.3 | 37 | 96 | 6.4 | 14.4 | |
| 31 | 9 | 608 | 59.9 | 1970 | 1780 | 148 | 292 | 7.84 | 31.7 | 2.2 | 32.3 | 109 | 12.3 | 7.91 | |
| 32 | 10 | 592 | 58.8 | 2058 | 1814 | 156 | 320 | 7.81 | 34.9 | 2 | 28.8 | 117 | 21.8 | 1.48 | |
| 33 | 11 | 600 | 60.5 | | | | | | | | | 129 | 17.6 | 0.4 | |
| 34 | 12 | 576 | 59.9 | 2098 | 1838 | 143 | 300 | 7.71 | | | | 113 | 16.8 | 0.58 | |
| 35 | 13 | 530 | 60.7 | 1816 | 1638 | 176 | 320 | 7.58 | 28.6 | 2.1 | 34 | 131 | 14.3 | 1.37 | |
| 36 | 14 | 588 | 61.6 | 1782 | 1608 | 145 | 260 | 7.79 | 25.6 | 2.2 | 36.5 | 109 | 12.6 | 2.49 | |
| 37 | 15 | 594 | 56 | | | | | | 16.3 | 2.6 | 71 | 125 | 14.6 | 4.6 | |
| 38 | 16 | 612 | 71.4 | 1122 | 926 | 160 | 180 | 7.8 | 16.2 | 2.6 | 76 | | | 5.7 | |
| 39 | 17 | 449 | 59.9 | | | | | | | | | 125 | 12.3 | 21.46 | |
| 40 | 18 | 563 | 66.1 | 1442 | 1312 | 125 | 180 | 7.58 | | | | 117 | 15.1 | 19.5 | |
| 41 | 19 | 477 | 59.4 | 1512 | 1352 | 105 | 160 | 7.71 | 21.5 | 2.5 | 61.2 | 125 | 19.3 | 16.83 | |
| 42 | 20 | 575 | 60.5 | 1060 | 930 | 113 | 120 | 7.65 | 16.8 | 2.7 | 37.4 | 145 | 25.8 | 10.75 | |
| 43 | 21 | 498 | 68.9 | 1856 | 1614 | 97 | 180 | 7.78 | 25.4 | 2.4 | 36.3 | 154 | 28.8 | 1.16 | |
| 44 | 22 | 596 | 60.2 | 2016 | 1884 | 79 | 160 | 7.76 | 20.1 | 2.3 | 45.3 | 117 | 19.3 | 0.62 | |
| 45 | 23 | 575 | 68.3 | | | | | 7.75 | | | | 115 | 15.7 | 1.1 | |
| 46 | 24 | 621 | 61.9 | | | | | | | | | 111 | 10.6 | 11.18 | |
| 47 | 25 | 629 | 60 | | | | | 7.72 | | | | 117 | 12.6 | 9.6 | |
| 48 | 26 | 502 | 64.1 | | | | | | | | | 101 | 10.1 | 10.51 | |
| 49 | 27 | 567 | 73.1 | 1532 | 1306 | 91 | 140 | 7.69 | 18.1 | | | 95 | 10.9 | 11.12 | |
| 50 | 28 | 587 | 57 | 1302 | 1206 | 108 | 140 | 7.66 | 17.5 | 2.6 | 41.4 | 97 | 16.5 | 10.05 | |
| 51 | 29 | 631 | 61.6 | 1312 | 1210 | 107 | 140 | 7.79 | 15.6 | 2.8 | 52 | 105 | 19.6 | 3.1 | |
| 52 | 30 | 603 | 54.9 | 1460 | 1248 | 109 | 160 | 7.8 | 15.1 | 2.8 | 47.3 | 176 | 27.2 | 1.05 | |

Month; July 1989

| | | Influent | | CFR 1 | | | | | | | | Effluents | | | Infl. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Day | Date | COD mg/l | TKN mg/l | MLSS mg/l | VSS mg/l | DSVI ml/g | Sett ml/l | pH | OUR | Peak | Aerob % | COD mg/l | TKN mg/l | NO3 mg/l | NO3 |
| 53 | 1 | 662 | 59.1 | 2560 | 2322 | 70 | 180 | 7.45 | 49.7 | 2.2 | 23.3 | 180 | 22.7 | 0 | |
| 54 | 2 | 499 | 53.5 | | | | | | | | | 155 | 12.3 | 0.19 | |
| 55 | 3 | 564 | 61.3 | 1988 | 1766 | 80 | 160 | 7.68 | 23.8 | 2.5 | 58 | 131 | 14.6 | 5.18 | |
| 56 | 4 | 548 | 55.4 | 2246 | 2040 | 71 | 160 | 7.79 | 20.3 | 2.43 | 29.3 | 139 | 17.4 | 1.46 | |
| 57 | 5 | 572 | 57.1 | 1426 | 1322 | 112 | 160 | 7.75 | 14.9 | 2.7 | 47 | 117 | 19.3 | 1.49 | |
| 58 | 6 | 517 | 56.3 | 1614 | 1488 | 86 | 140 | 7.88 | 18.3 | 2.8 | 42 | 129 | 20.7 | 1.1 | |
| 59 | 7 | 476 | 54.9 | 1436 | 1316 | 84 | 120 | 7.84 | 17.7 | 2.6 | 38.7 | 121 | 20.4 | 1.35 | |
| 60 | 8 | 611 | 58.5 | | | | | | | | | 129 | 22 | 1.3 | |
| 61 | 9 | 566 | 55.4 | | | | | 7.81 | 23.7 | 2.5 | 27.6 | 104 | 21.6 | 1.38 | |
| 62 | 10 | 570 | 57.1 | 1160 | 1092 | 103 | 120 | 7.71 | 17.1 | 2.7 | 60 | 119 | 21.6 | 1.13 | |
| 63 | 11 | 556 | 55.2 | | | | | | 22.7 | 2.56 | | 110 | 20.7 | 2.4 | |
| 64 | 12 | 515 | 60 | | | | | | | | | 102 | 21.8 | 1.75 | |
| 65 | 13 | 421 | 56.8 | | | | | | | | | 110 | 30 | 1.72 | |
| 66 | 14 | 421 | 56.8 | | | | | | | | | 127 | 25.5 | 0.79 | |
| 67 | 15 | 535 | 58.5 | | | | | | | | | 139 | 20.7 | 0.65 | |
| 68 | 16 | 568 | 58.2 | 2312 | 2096 | 87 | 200 | 7.83 | 29 | 2.7 | 33 | 123 | 21.6 | 0.6 | |
| 69 | 17 | 572 | 61.3 | 1436 | 1352 | 97.5 | 140 | 7.81 | 19.5 | 2.2 | 39.3 | 119 | 18.5 | 0.35 | |
| 70 | 18 | 237 | 51 | 2172 | 2056 | 83 | 180 | 7.72 | 26.5 | 2.3 | 29.3 | 131 | 25.5 | 0.64 | |
| 71 | 19 | 630 | 58.2 | 1916 | 1790 | 73 | 140 | 7.7 | 17.6 | 2.3 | 44 | 130 | 23.2 | 1.11 | |
| 72 | 20 | 557 | 56.6 | 1322 | 1280 | 106 | 140 | 7.74 | 22.3 | 1.98 | 30 | 114 | 26.3 | 1.69 | |
| 73 | 21 | 544 | 56 | | | | 140 | 7.7 | 22.7 | 2.3 | 33.3 | 139 | 24.6 | 0.64 | |
| 74 | 22 | 527 | 58.8 | 1862 | 1712 | 67 | 125 | 7.62 | 26.2 | 2 | 22.3 | 143 | 28.3 | 0.44 | |
| 75 | 23 | 589 | 58 | 3030 | 2802 | 53 | 160 | 7.66 | 28.2 | 1.9 | 21 | 172 | 31.4 | 0.24 | |
| 76 | 24 | 601 | 56.6 | 2472 | 2312 | 57 | 140 | 7.73 | 39.4 | 2.3 | 29.3 | 150 | 25.5 | 0.24 | |
| 77 | 25 | 606 | 63.6 | 2614 | 2410 | 71 | 185 | 7.74 | 24 | 2.5 | 37.6 | 163 | 24.4 | 0.29 | |
| 78 | 26 | 557 | 57.1 | 1830 | 1684 | 77 | 140 | 7.78 | 23 | 1.9 | 28 | 150 | 21.8 | 0.28 | |
| 79 | 27 | 589 | 61.3 | 1300 | 1236 | 86 | 110 | 7.76 | 14.9 | 2.2 | 50 | 126 | 25.2 | 0.24 | 62.61 |
| 80 | 28 | 593 | 56 | 1566 | 1448 | 77 | 120 | 7.75 | 18.2 | 2.1 | 40.6 | | | 12.3 | 51.43 |
| 81 | 29 | 577 | 58 | | | | | | | | | 93 | 15.1 | | 51.4 |
| 82 | 30 | 557 | 58 | 1800 | 1632 | 83 | 150 | | | | | 102 | 13.4 | 26.2 | 33.78 |
| 83 | 31 | 573 | 59.4 | 1402 | 1294 | 78 | 110 | 7.65 | 14 | 2.1 | 50 | 118 | 3.1 | 31.6 | 40 |

Month: August 1989

| | | Influent | | CFR 1 | | | | | | | | Effluents | | | Infl. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Day | Date | COD mg/l | TKN mg/l | MLSS mg/l | VSS mg/l | DSVI ml/g | Sett ml/l | pH | OUR | Peak | Aerob. % | COD mg/l | TKN mg/l | NO3 mg/l | NO3 mg/l |
| 84 | 1 | 565 | 63.6 | 1170 | 1096 | 103 | 120 | 7.8 | 11.7 | 2.7 | 42 | 122 | 22.7 | 20.6 | 48 |
| 85 | 2 | 630 | | 1254 | 1136 | 80 | 100 | 7.68 | 11.4 | 2.4 | 43 | 110 | 44.8 | 18.3 | 45.82 |
| 86 | 3 | 585 | 54 | 1472 | 1386 | 95 | 140 | 7.43 | 14.2 | 2.4 | 34 | 164 | 36.7 | 14.6 | 48.96 |
| 87 | 4 | 664 | 56.8 | 1974 | 1870 | 66 | 130 | 7.55 | 13.2 | 2.4 | 33 | 127 | 36.1 | 13.6 | 49 |
| 88 | 5 | 578 | 63 | | | | | | | | | 127 | 33 | 12.3 | 0 |
| 89 | 6 | | | 1786 | 1620 | 90 | 160 | 7.62 | 16.6 | 2.3 | 29 | | | 9.8 | 46.53 |
| 90 | 7 | 569 | 58 | | | | | | | | | 131 | 21 | | 46.5 |
| 91 | 8 | 553 | 58.5 | 1314 | 1178 | 99 | 130 | 7.62 | 16.3 | 2 | 24 | 115 | 28.6 | 20.3 | 39.72 |
| 92 | 9 | 586 | 61 | 1350 | 1230 | 96 | 130 | 7.66 | 14.4 | 2.3 | 33 | 115 | 30.2 | 12 | 6.72 |
| 93 | 10 | 324 | 46 | 1698 | 1566 | 71 | 120 | 7.72 | 13.5 | 2.3 | 32 | 98 | 20.7 | 7.4 | 45 |
| 94 | 11 | 610 | 52.4 | 2038 | 1892 | 69 | 140 | 7.67 | 19.9 | 2.2 | 22 | 127 | 19.3 | 8.4 | |
| 95 | 12 | 512 | 55.2 | | | | | | | | | 102 | | 9 | 45 |
| 96 | 13 | 578 | 46.5 | | | | | | | | | 95 | 3.1 | | 45 |
| 97 | 14 | 547 | 59.1 | 2228 | 2062 | 67 | 150 | 7.69 | 22.1 | 2.2 | 18.2 | 103 | 23.8 | 9.5 | 49.09 |
| 98 | 15 | 588 | 56.6 | 1524 | 1412 | 79 | 120 | 7.78 | 13 | 2.2 | 32.4 | 107 | 23.8 | 6.1 | 49.09 |
| 99 | 16 | 559 | 59.4 | 2862 | 2614 | 66 | 190 | 7.75 | 21.2 | 2.1 | 17.5 | 103 | 17.6 | 6.6 | 31.3 |
| 100 | 17 | 563 | 58.2 | 2422 | 2184 | 74 | 180 | 7.41 | 17.1 | 2.1 | 22.2 | 99 | 23.8 | 5.3 | 54.55 |
| 101 | 18 | 543 | 56.6 | 1938 | 1818 | 83 | 160 | 7.78 | 14.9 | 2.1 | 24.4 | 129 | 24.1 | 3.1 | 37.24 |
| 102 | 19 | 572 | 56 | | | | | | | | | 125 | 26 | 4.9 | 37.2 |
| 103 | 20 | 592 | 57.4 | | | | | | 21.7 | 2.1 | 17 | 113 | 32.2 | 1.4 | 50.53 |
| 104 | 21 | 555 | 54 | 1726 | 1516 | 87 | 150 | 7.76 | 20.6 | 2 | 16.4 | 113 | 23.2 | 4.1 | 45.82 |
| 105 | 22 | 604 | 57.4 | 2550 | 2274 | 63 | 160 | 7.87 | 20.5 | 2.2 | 31.6 | 109 | 26 | 7.4 | 43.85 |
| 106 | 23 | 596 | 51.2 | | | | | | | | | 77 | 17.1 | 8.1 | 43.8 |
| 107 | 24 | 558 | 59 | 3130 | 2748 | 61 | 190 | 7.68 | 21.8 | 1.8 | 25.6 | 77 | 21.8 | 9.2 | 31.58 |
| 108 | 25 | 582 | 58 | 2386 | 2122 | 80 | 190 | 7.81 | 18.5 | 1.9 | 28.7 | 69 | 24.4 | 6.3 | 33.96 |
| 109 | 26 | 542 | 57.7 | | | | | | | | | 106 | 23.5 | | 34 |
| 110 | 27 | 517 | 57.8 | 2498 | 2244 | 88 | 220 | 7.77 | 17.6 | 1.8 | 30.8 | 98 | 36.7 | 3.6 | 51.06 |
| 111 | 28 | 586 | 61 | 2280 | 2122 | 88 | 200 | 7.77 | 24.4 | 1.9 | 24 | 105 | 32.5 | 5.5 | 54 |
| 112 | 29 | 557 | 51.2 | 1990 | 1828 | 90 | 180 | 7.73 | 18.1 | 2.1 | 37 | 97 | 24.1 | 4.6 | 44.25 |
| 113 | 30 | 578 | 57.4 | 1706 | 1532 | 94 | 160 | 7.69 | 18.5 | 2.1 | 36 | 88 | 21.6 | 12 | 46.8 |
| 114 | 31 | 590 | 58.5 | 2356 | 2094 | 76 | 180 | 7.77 | 25.3 | 1.8 | 26 | 88 | 23 | 18.8 | 43 |

Month: September 1989

| | | Influent | | CFR 1 | | | | | | | | Effluents | | | Infl. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Day | Date | COD mg/l | TKN mg/l | MLSS mg/l | VSS mg/l | DSVI ml/g | Sett ml/l | pH | OUR | Peak DO | Aerob. % | COD mg/l | TKN mg/l | NO3 mg/l | NO3 mg/l |
| 115 | 1 | 586 | 56.8 | | | | | | | | | 88 | 23.2 | 13.4 | |
| 116 | 2 | 602 | 56.6 | | | | | | | | | 99 | 21 | 11.6 | |
| 117 | 3 | 575 | 59.1 | | | | | | | | | 105 | 17.9 | 11.6 | |
| 118 | 4 | 595 | 58.8 | 1932 | 1744 | 68 | 132 | 7.76 | | | | | | 20.2 | 45 |

Month; May 1989

| Day | Date | Influent COD mg/l | Influent TKN mg/l | ANOX 1 MLSS mg/l | ANOX 1 VSS mg/l | ANOX 1 SSVI ml/g | ANOX 1 Sett ml/l | ANOX 1 pH | Effluents COD mg/l | Effluents TKN mg/l | Effluents NO3 mg/l | Infl. NO3 mg/l |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | | | | | | | | | | | |
| | 2 | | | | | | | | | | | |
| | 3 | | | | | | | | | | | |
| | 4 | | | 718 | | 279 | 200 | 7.35 | | | | |
| | 5 | | | | | | | | | | | |
| | 6 | 480 | 69.7 | | | | | | 117 | 7.3 | 93.3 | |
| | 7 | | | | | | | | 125 | 3.1 | 85.8 | |
| | 8 | 439 | 61.3 | | | | | | | | | |
| | 9 | | | | | | | | | | | |
| 1 | 10 | | | | | | 220 | | 115 | 5.9 | 92.2 | |
| 2 | 11 | 464 | 60.5 | | | | 240 | 7.26 | 117 | | 99 | |
| 3 | 12 | 540 | 62.3 | 1250 | | 240 | 300 | 7.61 | 93 | | 108.7 | 156.4 |
| 4 | 13 | 472 | 63.1 | | | | | | 117 | 8.7 | 116.5 | |
| 5 | 14 | 484 | 66.6 | 1092 | 946 | 256 | 280 | 7.6 | 69 | 5.9 | 117.8 | 144 |
| 6 | 15 | 519 | 63 | 918 | 748 | 240 | 220 | 7.5 | 95 | 15 | 78.6 | 144 |
| 7 | 16 | 519 | 63.8 | 1332 | 1058 | 219 | 292 | 7.7 | 112 | 43 | 43 | 0 |
| 8 | 17 | 552 | 62.2 | 1914 | 1732 | 146 | 280 | 7.78 | 136 | 47 | 3.3 | 0 |
| 9 | 18 | 491 | 61.6 | 1616 | 1470 | 186 | 300 | 7.61 | 118 | 48 | 86.8 | 144 |
| 10 | 19 | 535 | 63.3 | 1690 | 1408 | 178 | 300 | 7.54 | 126 | 38 | 126.4 | 144 |
| 11 | 20 | 527 | 69.7 | 2100 | 1488 | 152 | 320 | 7.64 | 121 | 44 | 153.1 | 164.5 |
| 12 | 21 | 794 | 99 | 1886 | 1528 | 159 | 300 | 7.62 | 103 | 42 | 129.4 | 144 |
| 13 | 22 | | | 1824 | 1570 | 154 | 280 | 7.67 | 101 | 44 | 76.6 | 102.8 |
| 14 | 23 | 632 | 59.6 | 1892 | 1562 | 159 | 300 | 7.67 | 127 | 47 | 83.2 | 123.4 |
| 15 | 24 | 661 | 59 | 2360 | 2022 | 127 | 300 | 7.49 | 119 | 40 | 57.5 | 133.8 |
| 16 | 25 | 566 | 57.1 | 1964 | 1700 | 143 | 280 | 7.51 | 115 | 38 | 103.1 | 154.4 |
| 17 | 26 | 472 | 64.7 | 2120 | 1880 | 132 | 280 | 7.53 | 125 | 44 | 93.9 | 123.4 |
| 18 | 27 | 570 | 61.6 | | | | | | 131 | 38 | 85.3 | 144 |
| 19 | 28 | 554 | 60 | 2096 | 1856 | 134 | 280 | 7.61 | 118 | 33 | 118.2 | 144 |
| 20 | 29 | 513 | 57.4 | 2594 | 2274 | 108 | 280 | 7.58 | 122 | 32 | 113 | 144 |
| 21 | 30 | 533 | 58.2 | 2426 | 2098 | 115 | 280 | 7.54 | 130 | 38 | 113 | 144 |
| 22 | 31 | 546 | 60.3 | 2458 | 2164 | 114 | 280 | 7.57 | 163 | 28 | 115.6 | 115.3 |

Month; June 1989

| Day | Date | Influent COD mg/l | Influent TKN mg/l | ANOX 1 MLSS mg/l | ANOX 1 VSS mg/l | ANOX 1 DSVI ml/g | ANOX 1 Sett ml/l | pH | Effluents COD mg/l | Effluents TKN mg/l | Effluents NO3 mgN/l | Infl. NO3 mgN/l |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 23 | 1 | 643 | 60.2 | 2096 | 1866 | 134 | 280 | 7.4 | 130 | 39.8 | 108.6 | 140.6 |
| 24 | 2 | 652 | 57.7 | 2122 | 1850 | 132 | 280 | 7.41 | 113 | 26.9 | 128 | 146.4 |
| 25 | 3 | 491 | 57.7 | | | | | 7.43 | 109 | 39.5 | 129.5 | 123.4 |
| 26 | 4 | 516 | 56.3 | | | | | | 125 | 33.3 | 131.7 | 123.4 |
| 27 | 5 | 639 | 58.5 | 2228 | 2014 | 117 | 260 | 7.43 | 117 | 34.7 | 113 | 131.5 |
| 28 | 6 | 594 | 59.1 | 2544 | 2092 | 102 | 260 | 7.48 | 129 | 34.4 | 118.9 | 139.9 |
| 29 | 7 | 604 | 57.1 | | | | | 7.35 | 133 | 39.5 | 118.2 | 123.4 |
| 30 | 8 | 539 | 48.7 | 2200 | 1930 | 133 | 292 | 7.3 | 121 | 34.7 | 31 | 0 |
| 31 | 9 | 608 | 59.9 | 2224 | 2042 | 125 | 280 | 7.56 | 129 | 35.3 | 20.5 | 144 |
| 32 | 10 | 592 | 58.8 | 2074 | 1850 | 135 | 280 | 7.46 | 166 | 38.1 | 90.6 | 144 |
| 33 | 11 | 600 | 60.5 | | | | | | 150 | | 83.2 | 146 |
| 34 | 12 | 576 | 59.9 | 2156 | 1812 | 130 | 280 | 7.41 | 133 | 38.1 | 85.8 | 146 |
| 35 | 13 | 530 | 60.7 | 2320 | 2108 | 121 | 280 | 7.38 | 129 | 31.1 | 83.2 | 144 |
| 36 | 14 | 588 | 61.6 | 2196 | 1924 | 128 | 280 | 7.42 | 133 | 26 | 80.2 | 155.5 |
| 37 | 15 | 594 | 56 | | | | | | 104 | 33.9 | 87.3 | 135.8 |
| 38 | 16 | 612 | 71.4 | 2212 | 1884 | 127 | 280 | 7.49 | 145 | 38.4 | 81.2 | 144 |
| 39 | 17 | 449 | 59.9 | | | | | | 129 | 28.3 | 91.6 | 148.9 |
| 40 | 18 | 563 | 66.1 | 2224 | 1978 | 134.9 | 300 | 7.4 | 125 | 29.1 | 90.5 | 148.9 |
| 41 | 19 | 477 | 59.4 | 2186 | 1898 | 137 | 300 | 7.47 | 117 | 37.5 | 102.8 | 144 |
| 42 | 20 | 575 | 60.5 | 1944 | 1700 | 148 | 298 | 7.33 | 125 | 33 | 94.8 | 144 |
| 43 | 21 | 498 | 68.9 | 2066 | 1746 | 145 | 300 | 7.39 | 117 | 23.2 | 99.3 | 82.26 |
| 44 | 22 | 596 | 60.2 | 1940 | 1648 | 155 | 300 | 7.39 | 133 | 29.1 | 102.8 | 131.5 |
| 45 | 23 | 575 | 68.3 | | | | | 7.41 | 136 | 33 | 101.6 | 153.9 |
| 46 | 24 | 621 | 61.9 | | | | | | 128 | 33 | 92.7 | 135.6 |
| 47 | 25 | 629 | 60 | 1764 | 1538 | 188 | 332 | 7.54 | 115 | 33.9 | 100.5 | 131.5 |
| 48 | 26 | 502 | 64.1 | | | | | | 134 | 35 | 108.7 | 135.6 |
| 49 | 27 | 567 | 73.1 | 2146 | 1828 | 168 | 360 | 7.45 | 125 | 26 | 115 | 135.6 |
| 50 | 28 | 587 | 57 | 1786 | 1564 | 202 | 360 | 7.43 | 113 | 28.8 | 110.6 | 115.3 |
| 51 | 29 | 631 | 61.6 | 1900 | 1660 | 189 | 360 | 7.47 | 113 | 28 | 116.3 | 139.9 |
| 52 | 30 | 603 | 54.9 | 1830 | 1584 | 196 | 360 | 7.5 | 143 | 33.3 | 105.1 | 82.26 |

Month; July 1989

| | | Influent | | ANOX 1 | | | | | Effluents | | | Infl. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Day | Date | COD mg/l | TKN mg/l | MLSS mg/l | VSS mg/l | DSVI ml/g | Sett ml/l | pH | COD mg/l | TKN mg/l | NO3 mg/l | NO3 |
| 53 | 1 | 662 | 59.1 | 2512 | 2272 | 135 | 340 | 7.4 | 151 | 38.4 | 79.2 | 135.8 |
| 54 | 2 | 499 | 53.5 | | | | | | 155 | 32.2 | 17.8 | 0 |
| 55 | 3 | 564 | 61.3 | 2584 | 2300 | 124 | 320 | 7.35 | 168 | 31.9 | | 148 |
| 56 | 4 | 548 | 55.4 | 2362 | 2086 | 161 | 380 | 7.43 | 155 | 35.8 | 61.4 | 123.4 |
| 57 | 5 | 572 | 57.1 | 2670 | 2450 | 142 | 380 | 7.5 | 206 | 31.1 | 51.6 | 41.36 |
| 58 | 6 | 517 | 56.3 | 2598 | 2420 | 169 | 440 | 7.32 | 243 | 38.9 | 0.1 | 0 |
| 59 | 7 | 476 | 54.9 | 2784 | 2596 | 144 | 400 | 7.44 | 178 | 42 | 0.1 | 62.6 |
| 60 | 8 | 611 | 58.5 | | | | | | 182 | 35.6 | 1.13 | 61.02 |
| 61 | 9 | 566 | 55.4 | | | | | 7.33 | 227 | 35 | 0.16 | 59.21 |
| 62 | 10 | 570 | 57.1 | 1782 | 1688 | 303 | 540 | 7.36 | 180 | 31.6 | 0.21 | 56.95 |
| 63 | 11 | 556 | 55.2 | | | | | | 188 | 38.1 | 1.43 | 57.63 |
| 64 | 12 | 515 | 60 | | | | | | 139 | 36.1 | 4.74 | 56.5 |
| 65 | 13 | 421 | 56.8 | | | | | | 159 | 40.6 | 9.23 | 56.5 |
| 66 | 14 | 421 | 56.8 | | | | | | 172 | 36.4 | 5.82 | 56.5 |
| 67 | 15 | 535 | 58.5 | | | | | | 155 | 33 | 0.22 | 56.5 |
| 68 | 16 | 568 | 58.2 | 1686 | 1524 | 380 | 640 | 7.53 | 151 | 31.9 | 0.92 | 57.63 |
| 69 | 17 | 572 | 61.3 | 1970 | 1814 | 305 | 600 | 7.52 | 139 | | 1.49 | 52.66 |
| 70 | 18 | 237 | 51 | 1828 | 1716 | 372 | 680 | 7.59 | 188 | 42.6 | 16.16 | 74.13 |
| 71 | 19 | 630 | 58.2 | 1586 | 1462 | 340 | 540 | 7.58 | 98 | | 0.09 | 79.1 |
| 72 | 20 | 557 | 56.6 | 2120 | 1960 | 396 | 840 | 7.54 | 151 | 44.2 | 10.5 | 98.76 |
| 73 | 21 | 544 | 56 | | | | 600 | 7.51 | 143 | 42.3 | 35.2 | 122 |
| 74 | 22 | 527 | 58.8 | 1654 | 1488 | 411 | 680 | 7.55 | 139 | | 41.5 | 108.7 |
| 75 | 23 | 589 | 58 | 1486 | 1310 | 376 | 600 | 7.51 | 127 | 40 | 68 | 122 |
| 76 | 24 | 601 | 56.6 | 1628 | 1486 | 344 | 560 | 7.44 | 126 | 41.4 | 60.7 | 115.3 |
| 77 | 25 | 606 | 63.6 | 1652 | 1494 | 375 | 620 | 7.43 | 126 | 39.2 | 52.5 | 107.1 |
| 78 | 26 | 557 | 57.1 | 1872 | 1730 | 246 | 460 | 7.44 | 118 | 36.1 | 51 | 117.5 |
| 79 | 27 | 589 | 61.3 | 1856 | 1744 | 302 | 560 | 7.52 | 122 | 36.7 | 45 | 105.3 |
| 80 | 28 | 593 | 56 | 1972 | 1854 | 264 | 520 | 7.4 | | | 46.3 | 98.76 |
| 81 | 29 | 577 | 58 | | | | | | 114 | 33.3 | | 98.76 |
| 82 | 30 | 557 | 58 | 1980 | 1768 | 303 | 600 | | 126 | 32.5 | 14.2 | 98.76 |
| 83 | 31 | 573 | 59.4 | 1638 | 1478 | 297 | 480 | 7.42 | 126 | 38.6 | 64.9 | 104 |

Month; August 1989

| Day | Date | Influent COD mg/l | Influent TKN mg/l | ANOX 1 MLSS mg/l | ANOX 1 VSS mg/l | ANOX 1 DSVI ml/g | ANOX 1 Sett ml/l | ANOX 1 pH | Effluents COD mg/l | Effluents TKN mg/l | Effluents NO3 mg/l | Infl. NO3 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 84 | 1 | 565 | 63.6 | 1688 | 1544 | 261 | 440 | 7.4 | 126 | 35.6 | 51.8 | 112.1 |
| 85 | 2 | 630 | | 2040 | 1866 | 216 | 440 | 7.38 | 122 | 50.1 | 18.8 | 16.5 |
| 86 | 3 | 585 | 54 | 1602 | 1436 | 287 | 460 | 7.17 | 160 | 53.8 | 19.3 | 98.76 |
| 87 | 4 | 664 | 56.8 | 1504 | 1402 | 266 | 400 | 7.35 | 139 | 45.4 | 45.5 | 98.76 |
| 88 | 5 | 578 | 63 | | | | | | 111 | 41.4 | 50.3 | 84.07 |
| 89 | 6 | | | 1614 | 1430 | 273 | 440 | 7.33 | | | | 84.07 |
| 90 | 7 | 569 | 58 | | | | | | 135 | 35.6 | 54.1 | |
| 91 | 8 | 553 | 58.5 | 1892 | 1706 | 233 | 440 | 7.4 | 98 | 31.1 | 69.5 | 98.99 |
| 92 | 9 | 586 | 61 | 1816 | 1650 | 231 | 420 | 7.38 | 119 | 35.6 | 60 | 95.6 |
| 93 | 10 | 324 | 46 | 1836 | 1624 | 218 | 400 | 7.37 | 94 | 28.8 | 58 | 94.24 |
| 94 | 11 | 610 | 52.4 | 1808 | 1650 | 221 | 400 | 7.43 | 111 | 32.2 | 38.3 | |
| 95 | 12 | 512 | 55.2 | | | | | | 111 | 28.3 | 35.7 | |
| 96 | 13 | 578 | 46.5 | | | | | | 99 | 38.4 | 28.1 | |
| 97 | 14 | 547 | 59.1 | 2024 | 1864 | 198 | 400 | 7.39 | 103 | 34.4 | 17.8 | 32.77 |
| 98 | 15 | 588 | 56.6 | 1990 | 1840 | 211 | 420 | 7.45 | 95 | 32.2 | 9.5 | 110.7 |
| 99 | 16 | 559 | 59.4 | 1936 | 1740 | 227 | 440 | 7.39 | 105 | 34.2 | 31.2 | 118.7 |
| 100 | 17 | 563 | 58.2 | 1850 | 1692 | 260 | 480 | 7.12 | 105 | 30 | 44.3 | 110.1 |
| 101 | 18 | 543 | 56.6 | 1490 | 1354 | 309 | 460 | 7.47 | 121 | 29.4 | 44.9 | 68.93 |
| 102 | 19 | 572 | 56 | | | | | | 190 | 36.1 | 40.2 | 69.16 |
| 103 | 20 | 592 | 57.4 | | | | | | 137 | 35.6 | 0.43 | 69.16 |
| 104 | 21 | 555 | 54 | 1648 | 1512 | 255 | 420 | 7.41 | 129 | 33.9 | 4.61 | 109.6 |
| 105 | 22 | 604 | 57.4 | 1762 | 1590 | 295 | 520 | 7.54 | 133 | 35.3 | 29.6 | 68.25 |
| 106 | 23 | 596 | 51.2 | | | | | | 81 | 29.4 | 34.1 | |
| 107 | 24 | 558 | 59 | 1644 | 1464 | 316 | 520 | 7.46 | 98 | 26 | 37.4 | 102.2 |
| 108 | 25 | 582 | 58 | 1732 | 1558 | 323 | 560 | 7.54 | 98 | 34.2 | 40.2 | 83.17 |
| 109 | 26 | 542 | 57.7 | | | | | | 106 | 33.9 | 33.7 | 79.1 |
| 110 | 27 | 517 | 57.8 | 1788 | 1602 | 268 | 480 | 7.47 | 102 | 28.8 | 33.7 | 79.1 |
| 111 | 28 | 586 | 61 | 2334 | 2212 | 188 | 440 | 7.44 | 121 | 37.8 | 1.5 | 75.71 |
| 112 | 29 | 557 | 51.2 | 1722 | 1594 | 255 | 440 | 7.49 | 117 | | 21.3 | 31.41 |
| 113 | 30 | 578 | 57.4 | 2056 | 1862 | 214 | 440 | 7.44 | 121 | | 29.6 | 129.3 |
| 114 | 31 | 590 | 58.5 | 1826 | 1610 | 240 | 440 | 7.5 | 105 | | | 104.2 |

Month: September 1989

| Day | Date | Influent COD mg/l | Influent TKN mg/l | ANOX 1 MLSS mg/l | ANOX 1 VSS mg/l | ANOX 1 DSVI ml/g | ANOX 1 Sett ml/l | ANOX 1 pH | Effluents COD mg/l | Effluents TKN mg/l | Effluents NO3 mg/l | Infl. NO3 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 115 | 1 | 586 | 56.8 | | | | | | 93 | 35.6 | 87.3 | |
| 116 | 2 | 602 | 56.6 | | | | | | 113 | 35.6 | 60.4 | |
| 117 | 3 | 575 | 59.1 | | | | | | 115 | 36.4 | 63.2 | |
| 118 | 4 | 595 | 58.8 | 1792 | 1598 | 234 | 420 | 7.48 | 105 | 31.1 | 56.3 | 89.95 |
| 119 | 5 | 595 | 59.4 | 1840 | 1622 | 217 | 400 | 8.33 | 284 | 50.1 | 53.8 | 105.3 |
| 120 | 6 | 473 | 58.5 | 2170 | 1996 | 184 | 400 | 8 | 138 | 40.9 | 4.6 | 101.9 |
| 121 | 7 | 595 | 62.2 | 1888 | 1706 | 222 | 420 | 7.56 | 109 | 34.2 | 61.7 | 105.5 |
| 122 | 8 | 644 | 56 | 2228 | 1966 | 180 | 400 | 7.6 | | | 47.3 | 112.1 |
| 123 | 9 | 648 | 58.8 | | | | | | | | | |
| 124 | 10 | 589 | 57.7 | | | | | | 128 | 31.9 | | |
| 125 | 11 | 553 | 58.2 | 2154 | 1912 | 204 | 440 | 7.45 | 123 | 34.7 | 53.4 | 109.8 |
| 126 | 12 | 686 | 56 | 2162 | 1958 | 204 | 440 | 7.59 | 128 | 37.8 | 65 | 105.5 |
| 127 | 13 | 472 | 55.4 | 2164 | 2006 | 194 | 420 | 7.68 | 103 | 35.6 | 85.2 | 105.5 |
| 128 | 14 | 524 | 59.4 | 2340 | 2100 | 171 | 400 | 7.57 | 128 | 20.6 | 72.5 | 118.7 |
| 129 | 15 | 561 | 58.5 | 2356 | 2150 | 178 | 420 | 7.51 | 123 | 36.7 | 82.2 | 122.9 |
| 130 | 16 | 544 | 56.6 | 2198 | 1990 | 218 | 480 | 7.43 | 111 | 36.1 | 75.6 | 115.3 |
| 131 | 17 | 532 | 57.7 | 2460 | 2192 | 195 | 480 | 7.55 | 79 | 33 | 63.2 | 115.3 |
| 132 | 18 | 469 | 62.4 | 2284 | 1990 | 245 | 560 | 7.58 | 81 | 34.2 | 61.7 | 117.1 |
| 133 | 19 | 457 | 56.8 | 1826 | 1604 | 163 | 480 | 7.58 | 71 | 38.4 | 77.8 | 103.1 |
| 134 | 20 | 380 | 55.4 | 1998 | 1838 | 240 | 480 | 7.58 | 71 | 40.3 | 85.2 | 118.7 |
| 135 | 21 | 478 | 62.4 | 1886 | 1678 | 257 | 480 | 7.57 | 75 | 38.9 | 47.3 | 75.71 |
| 136 | 22 | 505 | 56.6 | 2000 | 1780 | 230 | 460 | 7.61 | 91 | 39.8 | 40 | 90.4 |
| 137 | 23 | 506 | 56.6 | | | | 600 | 7.55 | 71 | 38.1 | 40 | 75.94 |
| 138 | 24 | 543 | 61.9 | | | | | | 71 | 36.1 | 40.4 | |
| 139 | 25 | 469 | 56.8 | | | | | | 69 | 38.9 | 32.9 | |
| 140 | 26 | 426 | 59.4 | 1822 | 1642 | 231 | 420 | 7.51 | 73 | 30.2 | 52.3 | 79.1 |
| 141 | 27 | 499 | 60.5 | 1724 | 1556 | 244 | 420 | 7.77 | 65 | 29.4 | 55.4 | 87.91 |
| 142 | 28 | 511 | 56.6 | 1854 | 1640 | 227 | 420 | 7.58 | 65 | 31.9 | 67.5 | 75.71 |
| 143 | 29 | 556 | 60.2 | | | | | | 89 | 34.7 | 55.1 | |
| 144 | 30 | 442 | 56.3 | | | | | | 105 | 19.4 | 52 | |

Month: October 1989

| Day | Date | Influent COD mg/l | Influent TKN mg/l | ANOX 1 MLSS mg/l | ANOX 1 VSS mg/l | ANOX 1 DSVI ml/g | ANOX 1 Sett ml/l | ANOX 1 pH | Effluents COD mg/l | Effluents TKN mg/l | Effluents NO3 mg/l | Infl. NO3 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 145 | 1 | 438 | 51.8 | | | | | | 89 | 36.7 | 37.8 | |
| 146 | 2 | 539 | 59.9 | 1756 | | [illegible] | 480 | 7.39 | 89 | 31.6 | 36.7 | |
| 147 | 3 | 556 | 52.9 | 2224 | 1994 | [illegible] | 480 | 7.47 | 97 | 31.9 | 35.7 | 72.32 |

## APPENDIX E

Steady State Data and COD Balances calculated for system CFR 1 operated during phase 1 of the investigation.

COD Balance Phase 1 System CFR 1

Q = 10 l/d
fcv = 1.48 mgCOD/mgVSS
Vo = 7.5 l
fn = 0.1 mgN/mgVSS
waste = 0.8 l/d

| Steady State Period | Day | to | Day | M(Sti) mg/d | M(Ste) mg/d | Mwaste mg/d | M(Oc) | M(Xv) waste | MXv mg/l | MXv mg | COD Mass Balance |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0 | | 15 | 5530.8 | 982.0 | 1675.4 | 872.2 | 1132.0 | 2264.0 | 16980 | 64 |
| 2 | 16 | | 30 | 5621.3 | 865.5 | 1488.9 | 1080.4 | 1006.0 | 2012.0 | 15090 | 61 |
| 3 | 31 | | 45 | 5622.0 | 1236.4 | 1123.2 | 1143.1 | 758.9 | 1517.8 | 11384 | 62 |
| 4 | 46 | | 60 | 5726.0 | 1268.7 | 1126.6 | 1056.1 | 761.2 | 1522.4 | 11418 | 60 |
| 5 | 61 | | 76 | 5255.6 | 1270.0 | 1356.0 | 1048.8 | 916.2 | 1832.4 | 13743 | 70 |
| 6 | 77 | | 89 | 5895.0 | 1274.5 | 1131.0 | 1603.0 | 764.2 | 1528.4 | 11463 | 68 |
| 7 | 90 | | 105 | 5534.4 | 1115.0 | 1328.4 | 1523.5 | 897.5 | 1795.1 | 13463 | 72 |
| 8 | 106 | | 118 | 5741.5 | 914.2 | 1520.1 | 1777.2 | 1027.1 | 2054.3 | 15407 | 73 |
| | | | | | | | | | | Average | 66.3 |

| Steady State Period | Day | to | Day | M(Nd) mg/d | M(Nti) mg/d | M(Nni) mg/d | M(Nte) mg/d | M(Nne) mg/d | M(Nw) mg/d | M(Nnn) nit.gen |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0 | | 15 | 362.0 | 656.7 | | 136.2 | 45.4 | 113.2 | 407.3 |
| 2 | 16 | | 30 | 295.5 | 583.2 | | 88.9 | 98.2 | 100.6 | 393.7 |
| 3 | 31 | | 45 | 305.6 | 621.4 | | 175.9 | 64.0 | 75.9 | 369.6 |
| 4 | 46 | | 60 | 299.3 | 592.3 | | 171.3 | 45.8 | 76.1 | 345.1 |
| 5 | 61 | | 76 | 228.3 | 571.6 | | 241.8 | 9.9 | 91.6 | 238.2 |
| 6 | 77 | | 89 | 558.8 | 542.3 | 477.5 | 251.2 | 133.4 | 76.4 | 214.7 |
| 7 | 90 | | 105 | 641.2 | 557.7 | 417.7 | 228.9 | 75.4 | 89.8 | 239.0 |
| 8 | 106 | | 118 | 603.3 | 571.6 | 427.5 | 239.0 | 104.1 | 102.7 | 229.9 |

| Period | M(Otm) | OUR mgO/l/h | %Aerob | M(Od) | M(On) | |
|---|---|---|---|---|---|---|
| 1 | 1698.5 | 28.8 | 0.33 | 1035.2 | 1861.5 | 1861.5 |
| 2 | 2034.5 | 33.2 | 0.34 | 845.2 | 1799.4 | 1799.4 |
| 3 | 1958.1 | 33.7 | 0.46 | 874.1 | 1689.0 | 1689.0 |
| 4 | 1777.1 | 23.4 | 0.42 | 856.0 | 1577.0 | 1577.0 |
| 5 | 1484.3 | 24.6 | 0.34 | 853.0 | 1088.5 | 1088.5 |
| 6 | 986.1 | 15.5 | 0.35 | 1598.3 | 981.3 | 981.3 |
| 7 | 782.0 | 17.9 | 0.24 | 1833.7 | 1092.2 | 1092.2 |
| 8 | 1102.3 | 20.6 | 0.30 | 1725.6 | 1050.7 | 1050.7 |

# APPENDIX F

Experimental Data measured on systems ANOX 2 and ANOX 3 during phase 2 of the investigation.

Month; October 1989

| Day | Date | Influent COD mg/l | Influent TKN mg/l | ANOX 2 MLSS mg/l | ANOX 2 VSS mg/l | ANOX 2 DSVI ml/g | ANOX 2 Sett ml/l | pH | Effluents COD mg/l | Effluents TKN mg/l | Effluents NO3 mg/l | Infl. NO3 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 3 | 556 | 52.9 | 2224 | 1994 | 216 | 480 | 7.47 | 97 | 31.9 | 35.7 | 72.32 |
| 1 | 4 | 523 | 49.3 | 2188 | 2010 | 247 | 540 | 7.44 | 118 | 31.4 | 28.6 | 58.08 |
| 2 | 5 | 527 | 52.4 | 2042 | 1820 | 255 | 520 | 7.52 | 142 | 33.6 | 18.8 | 75.03 |
| 3 | 6 | 503 | 51.5 | 1900 | 1756 | 253 | 480 | 7.57 | 146 | 36.4 | 3.2 | 65.54 |
| 4 | 7 | 568 | 51 | | | | | | 115 | 31.9 | 0 | 67.12 |
| 5 | 8 | 484 | 50.7 | 2114 | 1886 | 208 | 440 | 7.57 | 119 | 30.8 | 6.8 | 79.1 |
| 6 | 9 | 496 | 51.5 | 2134 | 1888 | 206 | 440 | 7.58 | 107 | 30.8 | 23.4 | 86.33 |
| 7 | 10 | 496 | 51.2 | 2244 | 1986 | 178 | 400 | 7.65 | 115 | 31.6 | 29.1 | 67.35 |
| 8 | 11 | 496 | 49 | 2202 | 1914 | 173 | 380 | 7.62 | 128 | 31.6 | 29.1 | 56.5 |
| 9 | 12 | 504 | 47 | 2282 | 1998 | 153 | 350 | 7.69 | 124 | 28.6 | 21.1 | 96.28 |
| 10 | 13 | 488 | 46.5 | 2148 | 1864 | 140 | 300 | 7.57 | 108 | 29.4 | 20.5 | 75.26 |
| 11 | 14 | 467 | 46.8 | | | | | | 133 | 29.4 | 19.5 | |
| 12 | 15 | 473 | 45.6 | | | | | | 169 | 36.4 | 4.5 | |
| 13 | 16 | 488 | 45.1 | 2136 | 1864 | 140 | 300 | 7.61 | 141 | 23.8 | 18.5 | |
| 14 | 17 | 492 | 46.2 | 2100 | 1802 | 133 | 280 | 7.6 | 98 | 25.5 | 27 | 85.43 |
| 15 | 18 | 449 | 41.2 | 2018 | 1782 | 134 | 270 | 7.6 | 102 | 24.9 | 27.5 | 63.28 |
| 16 | 19 | 449 | 42.4 | 2040 | 1752 | 123 | 250 | 7.65 | 86 | 28.8 | 38.5 | 115.3 |
| 17 | 20 | 518 | 50.5 | 2052 | 1756 | 108 | 222 | 7.61 | 86 | 23 | 50 | 110.7 |
| 18 | 21 | 514 | 52.1 | | | | | | 90 | 28.6 | 70 | 113.7 |
| 19 | 22 | 547 | 50.1 | 1956 | 1728 | 96 | 189 | 7.6 | 107 | 31.9 | 65 | 113.7 |
| 20 | 23 | 644 | 50.4 | 1936 | 1640 | 97 | 188 | 7.62 | 113 | 31.4 | 52 | 91.3 |
| 21 | 24 | 574 | 48.4 | 2172 | 1882 | 81 | 176 | 7.75 | 115 | 33.5 | 46.5 | 99.67 |
| 22 | 25 | 566 | 47.8 | 2126 | 1774 | 88 | 188 | 7.57 | 125 | 32.8 | 35 | 93.11 |
| 23 | 26 | 562 | 49.2 | 2152 | 1838 | 82 | 176 | 7.69 | 125 | 29.9 | 28.5 | 83.62 |
| 24 | 27 | 587 | 49.9 | 2140 | 1832 | 80 | 172 | 7.67 | 102 | 31.4 | 24 | 84.75 |
| 25 | 28 | 600 | 55.2 | | | | | | 106 | 36.7 | 28.5 | 91.08 |
| 26 | 29 | 612 | 54.7 | 2156 | 1798 | 78 | 168 | 7.71 | 112 | 35.8 | 39 | 91.08 |
| 27 | 30 | 616 | 52.8 | 2204 | 1798 | 91 | 200 | 7.65 | 122 | 34.6 | 35 | 88.59 |
| 28 | 31 | 608 | 48.6 | 2190 | 1830 | 80 | 176 | 7.62 | 114 | 33.4 | 27 | 91.78 |

Month; October 1989

| | | Influent | | ANOX 3 | | | | | Effluents | | | Infl. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Day | Date | COD mg/l | TKN mg/l | MLSS mg/l | VSS mg/l | DSVI ml/g | Sett ml/l | pH | COD mg/l | TKN mg/l | NO3 mg/l | NO3 mg/l |
| 145 | 1 | 438 | 51.8 | | | | | | | | | |
| 146 | 2 | 539 | 59.9 | | | | | | | | | |
| 147 | 3 | 556 | 52.9 | | | | | | | | | |
| | PHASE 2 | | | | | | | | | | | |
| 0 | 3 | 556 | 52.9 | | | | | | | | | |
| 1 | 4 | 523 | 49.3 | 986 | 850 | 142 | 140 | 7.68 | 114 | 36.7 | 44.9 | 94.92 |
| 2 | 5 | 527 | 52.4 | 1042 | 830 | 154 | 160 | 7.63 | 118 | 22.1 | 105.3 | 134.5 |
| 3 | 6 | 503 | 51.5 | 1174 | 954 | 136 | 160 | 7.45 | 107 | 29.4 | 110.2 | 130.9 |
| 4 | 7 | 568 | 51 | | | | | | 115 | 33.9 | 84.2 | 118.7 |
| 5 | 8 | 484 | 50.7 | 1550 | 1316 | 116 | 180 | 7.56 | 99 | 34.2 | 11 | 125.2 |
| 6 | 9 | 496 | 51.5 | 1700 | 1408 | 113 | 192 | 7.4 | 121 | 34.4 | 43.2 | 127.2 |
| 7 | 10 | 496 | 51.2 | 1906 | 1602 | 105 | 200 | 7.61 | 115 | 35.8 | 44.4 | 73.68 |
| 8 | 11 | 496 | 49 | 1998 | 1670 | 100 | 200 | 7.57 | 111 | 38.1 | 32.6 | 113 |
| 9 | 12 | 504 | 47 | 2168 | 1810 | 92 | 200 | 7.62 | 100 | 32.2 | 53.3 | 137.6 |
| 10 | 13 | 488 | 46.5 | 2014 | 1678 | 99 | 200 | 7.6 | 104 | 33 | 52.5 | 113 |
| 11 | 14 | 467 | 46.8 | | | | | | 129 | 34.4 | 52 | |
| 12 | 15 | 473 | 45.6 | | | | | | 137 | 37.2 | 14.5 | |
| 13 | 16 | 488 | 45.1 | 2112 | 1754 | 85 | 180 | 7.6 | 116 | 34.2 | 60.5 | |
| 14 | 17 | 492 | 46.2 | 1938 | 1610 | 83 | 160 | 7.54 | 90 | 31.4 | 55 | 128.1 |
| 15 | 18 | 449 | 41.2 | 1930 | 1626 | 83 | 160 | 7.62 | 82 | 33 | 57.5 | 63.28 |
| 16 | 19 | 449 | 42.4 | 2004 | 1652 | 85 | 170 | 7.62 | 94 | | 48 | 125.2 |
| 17 | 20 | 518 | 50.5 | 1860 | 1512 | 83 | 155 | 7.58 | 96 | 34.4 | 91 | 126.6 |
| 18 | 21 | 514 | 52.1 | | | | | | 84 | 36.7 | 68.5 | 121.8 |
| 19 | 22 | 547 | 50.1 | 1944 | 1656 | 78 | 155 | 7.64 | 101 | 37.5 | 62.5 | 121.8 |
| 20 | 23 | 644 | 50.4 | 1964 | 1616 | 79 | 156 | 7.7 | 121 | 38.4 | 41 | 91.3 |
| 21 | 24 | 574 | 48.4 | 2180 | 1848 | 77 | 168 | 7.77 | 113 | 37.6 | 29 | 85.88 |
| 22 | 25 | 566 | 47.8 | 2144 | 1800 | 78 | 176 | 7.54 | 134 | 36.4 | 24 | 96.05 |
| 23 | 26 | 562 | 49.2 | | | | 168 | 7.72 | 130 | 35.2 | 26 | 97.63 |
| 24 | 27 | 587 | 49.9 | 2236 | 1874 | 77 | 172 | 7.68 | 98 | 35.7 | 27 | 97.18 |
| 25 | 28 | 600 | 55.2 | | | | | | 114 | 36.2 | 27 | 91.08 |
| 26 | 29 | 612 | 54.7 | 2084 | 1746 | 75 | 156 | 7.67 | 98 | 34.5 | 42 | 91.08 |
| 27 | 30 | 616 | 52.3 | 2212 | 1796 | 83 | 144 | 7.62 | 106 | 33.2 | 38.5 | 107.8 |
| 28 | 31 | 608 | 48.6 | 2056 | 1720 | 73 | 155 | 7.59 | 100 | 32.1 | 38.5 | 91.98 |

Month: November 1989

| | | Influent | | ANOX 2 | | | | | Effluents | | | Infl. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Day | Date | COD mg/l | TKN mg/l | MLSS mg/l | VSS mg/l | DSVI ml/g | Sett ml/l | pH | COD mg/l | TKN mg/l | NO3 mg/l | NO3 |
| 29 | 1 | 608 | 51.4 | 2878 | 2226 | 57 | 164 | 7.67 | 116 | 22.7 | 28 | 105.3 |
| 30 | 2 | 570 | 47 | 2136 | 1756 | 71 | 152 | 7.68 | 116 | 27.4 | 30 | 82.72 |
| 31 | 3 | 512 | 45.4 | | | | | 7.64 | 132 | 26.3 | 24 | 104 |
| 32 | 4 | 497 | 46.8 | 2110 | 1732 | 63 | 133 | 7.6 | 103 | 35.3 | 18.18 | 93.79 |
| 33 | 5 | 537 | 43.4 | | | | | | 95 | | 25.32 | 88.14 |
| 34 | 6 | 489 | 45.2 | 2076 | 1722 | 64 | 133 | 7.5 | 85 | | 24.46 | 88.14 |
| 35 | 7 | 451 | 38.1 | 2028 | 1694 | 68 | 139 | 7.56 | 89 | | 25.61 | 87.01 |
| 36 | 8 | 469 | 42.1 | 1848 | 1552 | 78 | 144 | 7.56 | 93 | | 25.61 | 103.5 |
| 37 | 9 | 459 | 38.7 | 2106 | 1770 | 71 | 150 | 7.48 | 89 | 31.6 | 21.46 | 75.26 |
| 38 | 10 | 532 | 47.3 | 2136 | 1826 | 59 | 125 | 7.64 | 89 | 33.9 | 19.16 | |
| 39 | 11 | 475 | 46.2 | | | | | | 89 | 34.2 | 20.42 | 86.56 |
| 40 | 12 | 557 | 46.5 | | | | | | 106 | 35 | 23.06 | 86.56 |
| 41 | 13 | 536 | 46.2 | 2070 | 1732 | 58 | 120 | 7.63 | 93 | 32.8 | 22.52 | 86.56 |
| 42 | 14 | 557 | 45.9 | 1932 | 1610 | 67 | 130 | 7.7 | 114 | 32.5 | 24.46 | 79.1 |
| 43 | 15 | 593 | 58 | 1894 | 1590 | 71 | 135 | 7.67 | 96 | | 20.16 | 91.3 |
| 44 | 16 | 601 | | | | | | | | | 20.04 | |
| 45 | 17 | | | | | | | | | | | |

Month: November 1989

| | | Influent | | ANOX 3 | | | | | Effluents | | | Infl. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Day | Date | COD mg/l | TKN mg/l | MLSS mg/l | VSS mg/l | DSVI ml/g | Sett ml/l | pH | COD mg/l | TKN mg/l | NO3 mg/l | NO3 mg/l |
| 29 | 1 | 608 | 51.4 | 3342 | 2554 | 43 | 144 | 7.6 | 91 | 31.4 | 45 | 101.5 |
| 30 | 2 | 570 | 47 | 2114 | 1740 | 68 | 144 | 7.66 | 99 | 31.4 | 36.5 | 100.6 |
| 31 | 3 | 512 | 45.4 | | | | | 7.65 | 107 | 32.8 | 32 | 84.75 |
| 32 | 4 | 497 | 46.8 | 2062 | 1756 | 65 | 133 | 7.58 | 107 | 32.5 | 22.5 | 93.79 |
| 33 | 5 | 537 | 43.4 | | | | | | 99 | 33.2 | 29.33 | 93.56 |
| 34 | 6 | 489 | 45.2 | 2038 | 1710 | 71 | 144 | 7.45 | 69 | 31.8 | 30.15 | 93.56 |
| 35 | 7 | 451 | 38.1 | 2020 | 1722 | 71 | 144 | 7.54 | 93 | 32.6 | 28.68 | 87.01 |
| 36 | 8 | 469 | 42.1 | 1962 | 1596 | 68 | 133 | 7.53 | 93 | 34.5 | 24.46 | 103.5 |
| 37 | 9 | 459 | 38.7 | 1994 | 1666 | 75 | 150 | 7.52 | 122 | 35.3 | 23.06 | 94.24 |
| 38 | 10 | 532 | 47.3 | 1918 | 1628 | 68 | 130 | 7.65 | 106 | 36.4 | 17.93 | |
| 39 | 11 | 475 | 46.2 | | | | | | 98 | 37.5 | 15.13 | 87.91 |
| 40 | 12 | 557 | 46.5 | | | | | | 93 | 36.4 | 24.74 | 87.91 |
| 41 | 13 | 536 | 46.2 | 1976 | 1650 | 66 | 130 | 7.67 | 106 | 33.3 | 19.41 | 87.91 |
| 42 | 14 | 557 | 45.9 | 1982 | 1606 | 66 | 135 | 7.72 | 93 | 31.6 | 22.52 | 79.1 |
| 43 | 15 | 593 | 58 | 1972 | 1666 | 66 | 130 | 7.66 | 104 | 33.8 | 15.82 | 109.6 |
| 44 | 16 | 601 | | | | | | | | | 20.16 | |
| 45 | 17 | | | | | | | | | | | |

# APPENDIX G

Steady State Data and COD Balances calculated for the fully anoxic systems ANOX 1, ANOX 2 and ANOX 3 operated during phase 1 and 2 of the investigation. Also presented are the COD utilisation rates calculated for systems ANOX 2 and ANOX 3 during phase 2.

D Balance Phase 1 & 2 Systems ANOX 1.2 & 3

= 10 l/d Rs = 15 days
v = 1.48 mgCOD/mgVSS
= 7.5 l
= 0.1 mgN/mgVSS
ste = 0.5 l/d

| Steady State Period | Day | to Day | M(Sti) mg/d | M(Ste) mg/d | %waste mg/d (COD) | M(Oc) = M(Od) (100%N) | M(Xv) mg/d (waste) | MXv mg/l (meas) | MXv mg (total) | COD Mass Balance (100%N) | M(Oc)' = M(Od) (N<100%) | COD Mass Balance' (N<100%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| OX 1 | | | | | | | | | | | | |
| 1 | 0 | 6 | 4958.0 | 1010.0 | 626.8 | 2839.4 | 423.5 | 847.0 | 6353 | 90.3 | | |
| 2 | 7 | 29 | 5729.1 | 1283.2 | 1244.4 | 1052.2 | 840.8 | 1681.6 | 12612 | 62.5 | 627.5 | 55.1 |
| 3 | 30 | 44 | 5598.0 | 1304.0 | 1388.7 | 1939.7 | 938.3 | 1876.7 | 14075 | 82.8 | 1399.4 | 73.1 |
| 4 | 45 | 55 | 5854.5 | 1346.4 | 1347.4 | 1280.3 | 910.4 | 1820.9 | 13656 | 67.9 | 705.3 | 58.1 |
| 5 | 56 | 68 | 5289.2 | 1796.2 | 1574.2 | 1747.0 | 1063.7 | 2127.3 | 15955 | 96.8 | 1448.2 | 91.1 |
| 6 | 69 | 84 | 5546.3 | 1312.7 | 1207.8 | 2429.3 | 816.1 | 1632.1 | 12241 | 89.2 | 1820.7 | 78.3 |
| 7 | 85 | 99 | 5630.7 | 1144.3 | 1224.9 | 1627.3 | 827.6 | 1655.3 | 12415 | 71.0 | 1331.0 | 65.7 |
| 8 | 100 | 114 | 5690.0 | 1176.0 | 1214.3 | 2059.3 | 820.5 | 1640.9 | 12307 | 78.2 | 1601.0 | 70.1 |
| 9 | 115 | 129 | 5798.7 | 1300.0 | 1407.0 | 1711.7 | 950.7 | 1901.4 | 14261 | 76.2 | 1336.8 | 69.7 |
| 10 | 130 | 147 | 4916.7 | 812.2 | 1339.0 | 1575.1 | 904.7 | 1809.5 | 13571 | 75.8 | 1164.6 | 67.4 |
| OX 2 & 3 | | | | | | | | | Average | 79.1 | | 69.8 |
| 1 | 0 | 15 | 5006.3 | 1226.3 | 1398.3 | 1772.7 | 944.8 | 1889.5 | 14172 | 87.8 | 1524.7 | 82.9 |
| 2 | 16 | 30 | 5716.7 | 1090.0 | 1344.3 | 1529.5 | 908.1 | 1816.2 | 13621 | 76.3 | 1638.9 | 71.2 |
| 3 | 31 | 45 | 5189.3 | 979.2 | 1258.1 | 2027.9 | 846.0 | 1692.0 | 12690 | 82.1 | 1907.5 | 79.8 |
| 4 | 0 | 15 | 5006.3 | 1105.3 | 1083.0 | 1909.2 | 712.8 | 1425.7 | 10693 | 81.3 | 1675.9 | 76.6 |
| 5 | 16 | 30 | 5716.7 | 1052.7 | 1333.3 | 1960.8 | 895.6 | 1791.2 | 13434 | 75.9 | 1721.6 | 71.7 |
| 6 | 31 | 45 | 5189.3 | 992.3 | 1273.3 | 2049.8 | 835.0 | 1670.0 | 12525 | 82.4 | 1962.8 | 80.8 |
| | | | | | | | | | Average | 81.0 | | 77.2 |

| teady State eriod | M(Otm) | OUR mgO/l/h | %Aerob | M(Cd) | M(On) |
|---|---|---|---|---|---|
| 1 | 2149.2 | 39.8 | 0.3 | 2741.7 | 2031.473 |

n Calculations

| Day | to | Day | M(Nd) mg/d (100%N) | M(Nti) mg/d | M(Nni) mg/d | M(Nte) mg/d | M(Nne) mg/d | M(Nw) mg/d | M(Od) mg/d (100%N) | M(Nnn) mgN/d | TKN Balance | Nitrogen Balance | M(Nnd) mg/d (N<100%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | | 6 | 958.6 | 631.0 | 1481.1 | 89.8 | 1021.3 | 42.4 | 2741.7 | 449 | 92 | 100 | |
| 7 | | 29 | 367.9 | 620.1 | 1240.8 | 387.6 | 1021.4 | 84.1 | 1052.2 | | 76 | 92 | 219.4 |
| 30 | | 44 | 678.2 | 608.3 | 1305.8 | 325.6 | 816.5 | 93.8 | 1939.7 | | 69 | 90 | 489.3 |
| 45 | | 55 | 447.6 | 613.5 | 1194.1 | 321.4 | 947.5 | 91.0 | 1280.3 | | 67 | 89 | 246.6 |
| 56 | | 68 | 610.8 | 569.4 | 528.2 | 358.5 | 21.9 | 106.4 | 1747.0 | | 82 | 90 | 506.4 |
| 67 | | 84 | 849.4 | 583.4 | 1009.5 | 289.1 | 372.9 | 81.6 | 2429.3 | | 64 | 87 | 636.6 |
| 85 | | 99 | 569.0 | 558.8 | 848.3 | 372.5 | 382.9 | 82.8 | 1627.3 | | 81 | 93 | 465.4 |
| 100 | | 114 | 720.0 | 567.6 | 842.3 | 325.3 | 282.5 | 82.0 | 2059.3 | | 72 | 89 | 559.3 |
| 115 | | 129 | 598.5 | 580.9 | 1077.3 | 354.8 | 609.9 | 95.1 | 1711.7 | | 77 | 92 | 467.4 |
| 130 | | 147 | 550.7 | 578.2 | 938.7 | 344.2 | 531.4 | 90.5 | 1575.1 | | 75 | 91 | 407.2 |
| 3 | | | | | | | | | | | 74 | 90 | |
| 0 | | 15 | 619.8 | 486.2 | 728.9 | 305.0 | 195.8 | 94.5 | 1772.7 | | 82 | 93 | 533.1 |
| 16 | | 30 | 674.6 | 500.3 | 971.0 | 307.9 | 398.0 | 90.8 | 1929.5 | | 80 | 93 | 573.3 |
| 31 | | 45 | 709.0 | 453.7 | 891.6 | 327.0 | 224.6 | 84.6 | 2027.9 | | 91 | 97 | 667.0 |
| 0 | | 15 | 667.6 | 486.2 | 1133.4 | 333.3 | 547.4 | 71.3 | 1909.2 | | 83 | 95 | 586.3 |
| 16 | | 30 | 685.6 | 500.3 | 1031.6 | 327.1 | 429.7 | 89.6 | 1960.8 | | 83 | 95 | 601.7 |
| 31 | | 45 | 716.7 | 453.7 | 919.1 | 339.8 | 232.8 | 83.5 | 2049.8 | | 93 | 98 | 686.3 |
| | | | | | | | | | | | 85 | 95 | |

Kinetic Evaluation of Results

Yh = 0.45 /d
bh = 0.24 /d
f = 0.2
fcv = 1.48 mgCOD/mgVSS
Rs = 15 days

ANOX 2 & 3

fbs = 0.2 mgCOD/mgCOD
fus = 0.1 mgCOD/mgCOD

| | x | fup | MXv | MXa | fav | RBCODLRax | PBCODURax |
|---|---|---|---|---|---|---|---|
| 1 | 0.189 | 0.072 | 14123.8 | 6080.9 | 0.429 | 5.68 | 31.13 |
| 2 | 0.159 | 0.013 | 13564.6 | 7438.1 | 0.546 | 5.68 | 27.07 |
| 3 | 0.163 | 0.022 | 12638.9 | 6689.1 | 0.527 | 5.68 | 32.60 |
| 4 | 0.142 | -0.019 | 10641.9 | 6752.2 | 0.631 | 5.68 | 30.02 |
| 5 | 0.157 | 0.009 | 13377.0 | 7474.3 | 0.556 | 5.68 | 27.44 |
| 6 | 0.161 | 0.017 | 12473.8 | 6720.9 | 0.537 | 5.68 | 32.83 |

Month; April 1990

| | | Influent | | CFR 2 | | | | | | | | Effluents | | | Infl. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Day | Date | COD mg/l | TKN mg/l | MLSS mg/l | VSS mg/l | DSVI ml/g | Sett ml/l | pH | OUR mg/l/h | peak | aerob. % | COD mg/l | TKN mg/l | NO3 mg/l | NO3 mg/l |
| | 4 | | | | | | | | | | | | | | |
| 0 | 5 | 466 | 45.4 | | | | | | | | | 80 | 13.2 | 0 | 0 |
| 1 | 6 | 470 | 44.8 | 4072 | | 177 | 720 | 7.5 | | | | 68 | 16 | 0 | 0 |
| 2 | 7 | 470 | 45.1 | 3656 | | 186 | 680 | 7.7 | | | | 32 | 7.6 | 0.9 | 0 |
| 3 | 8 | 493 | 42.6 | | | | | | | | | 44 | 7.6 | 10.1 | 28.75 |
| 4 | 9 | 460 | 44 | 3660 | | 191 | 700 | 7.45 | 49.7 | 2.25 | 28 | 27 | 7.3 | 82.3 | 45 |
| 5 | 10 | 477 | 39.2 | 3586 | | 201 | 720 | 7.35 | 29.2 | 2.47 | 56 | 44 | 4.9 | | 34.56 |
| 6 | 11 | 434 | 36.1 | 3468 | 3086 | 190 | 660 | 7.3 | 26.3 | 2.7 | | 25 | 5.6 | | 36 |
| 7 | 12 | 472 | 37.2 | 2828 | 2480 | 212 | 600 | 7.55 | 34.4 | 1.9 | 27 | 74 | 5.18 | 63.2 | 26.09 |
| 8 | 13 | 598 | 47 | | | | | | | | | 34 | 3.64 | 59.4 | 26.05 |
| 9 | 14 | 533 | 45.9 | | | | | | | | | 34 | 4.2 | 48.3 | 35.6 |
| 10 | 15 | 586 | 52.1 | 3210 | 2836 | 187 | 600 | 7.6 | | | | 54 | 3.8 | 58.7 | 28.42 |
| 11 | 16 | 631 | 52.1 | 2856 | 2524 | 210 | 600 | 7.55 | 47.3 | 2.6 | 29 | 46 | 5.2 | 51.7 | 34.96 |
| 12 | 17 | 663 | 53.5 | 3102 | 2744 | 193 | 600 | 7.45 | 44.3 | 2.8 | 29 | 47 | 5.74 | 43.6 | 13.71 |
| 13 | 18 | 567 | 52.6 | 3136 | 2702 | 198 | 620 | 7.55 | 49.8 | 2.7 | 27 | 51 | 3.8 | 33 | 12.5 |
| 14 | 19 | 614 | 55.2 | 3190 | 2806 | 182 | 580 | 7.6 | 50 | 2.9 | 26.7 | 41 | 11.9 | 9.8 | 18.82 |
| 15 | 20 | 471 | 46.5 | 2786 | 2466 | 208 | 580 | 7.6 | 51.6 | 2.5 | 26.7 | 53 | 12.9 | 6.5 | 14 |
| 16 | 21 | 508 | 45.9 | | | | | | | | | 49 | 7.4 | 9 | 14 |
| 17 | 22 | 504 | | | | | | | | | | 45 | 4.8 | 19.5 | 14 |
| 18 | 23 | 462 | 46.5 | 3196 | 2828 | 181 | 580 | 7.5 | 49.4 | 2.5 | 29.3 | 47 | 3 | 17.3 | 17.05 |
| 19 | 24 | 539 | 42.4 | 2892 | 2554 | 207 | 600 | 7.55 | 57.5 | 2.4 | 24 | 41 | 2 | 16.1 | 17.78 |
| 20 | 25 | 470 | 40.5 | 3180 | 2826 | 189 | 600 | 7.55 | | | | 45 | 1 | 20.7 | 19.2 |
| 21 | 26 | 462 | 40.5 | 2856 | 2496 | 196 | 560 | 7.45 | 43.4 | 2.5 | 31 | 40 | 1.1 | 28.5 | 16.36 |
| 22 | 27 | 487 | 43.1 | 3080 | 2722 | 188 | 580 | 7.55 | 44.8 | 2.7 | 32 | 49 | 1.2 | 30.3 | 16.67 |
| 23 | 28 | 475 | 39.4 | | | | | | | | | 53 | 1 | 31.4 | 16.65 |
| 24 | 29 | 584 | 44.2 | | | | | | | | | 49 | 2.3 | 32.2 | 16.85 |
| 25 | 30 | 540 | 46.1 | 2576 | 2236 | 217 | 560 | 7.6 | 48.6 | 2.5 | 29.3 | 41 | 4.9 | 28.5 | 18.42 |

Month: May 1990

| | | Influent | | CFR 2 | | | | | | | | Effluents | | | Infl. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Day | Date | COD mg/l | TKN mg/l | MLSS mg/l | VSS mg/l | SVI ml/g | Sett ml/l | pH | OUR mg/l/h | peak | aerob. % | COD mg/l | TKN mg/l | NO3 mg/l | NO3 |
| 26 | 1 | 446 | 31.8 | | | | | | | | | 48 | 0.6 | 27 | 18.15 |
| 27 | 2 | 484 | 35.6 | 2814 | 2486 | 199 | 560 | 7.55 | 45.2 | 2.7 | 32.9 | 50 | 4.2 | 27.9 | 16.5 |
| 28 | 3 | 520 | 47.9 | 2690 | 2336 | 220 | 592 | 7.53 | 29.6 | 2.5 | 33.6 | 42 | 6.6 | 28.5 | 16.14 |
| 29 | 4 | 500 | 48.2 | 2946 | 2568 | 197 | 580 | 7.4 | 46 | 2.6 | 31 | 54 | 8.3 | 25.2 | 16.25 |
| 30 | 5 | 488 | 50.7 | | | | | | | | | 54 | 8.7 | 29.2 | 16.25 |
| 31 | 6 | 545 | 53.8 | | | | | | | | | 24 | 2 | 31.4 | 17.5 |
| 32 | 7 | 466 | 50.8 | 2580 | 2274 | 248 | 640 | 7.5 | | | | 41 | 2.4 | 29.2 | 18 |
| 33 | 8 | 564 | 58.1 | 2856 | 2524 | 217 | 620 | | 58.2 | 2.5 | 27 | 32 | 5.1 | 28.2 | 16 |
| 34 | 9 | 511 | 43.4 | 2442 | | 262 | 640 | 7.6 | 52.9 | 2.6 | 26.4 | 32 | 2.9 | 25.2 | 19 |
| 35 | 10 | 527 | 38.5 | 2608 | 2494 | 261 | 170 | 7.51 | 29.6 | 2.65 | 50 | 28 | 0.1 | 28.2 | 4 |
| 36 | 11 | 519 | 36.7 | 2646 | 2184 | 242 | 160 | 7.55 | | | | 33 | 0.1 | 27.3 | 21.05 |
| 37 | 12 | 506 | 33.6 | | | | | | | | | 37 | 0.4 | 28.9 | 21.05 |
| 38 | 13 | 604 | 37.9 | | | | | | | | | 37 | 0.5 | 26.7 | 21 |
| 39 | 14 | 518 | 39.5 | 2632 | 2284 | 258 | 680 | 7.45 | 36.9 | 2.7 | 37 | 41 | 3.6 | 24.1 | 19.2 |
| 40 | 15 | 518 | 40.1 | | | | | | | | | 45 | 2.9 | 24.1 | 19.2 |
| 41 | 16 | 518 | 45.4 | 3052 | 2648 | 223 | 680 | 7.55 | 43.7 | 2.6 | 32.9 | 43 | 6.6 | 21.9 | 19 |
| 42 | 17 | 544 | 49.3 | 2754 | 2294 | 240 | 660 | 7.54 | 60 | | 27 | 51 | 3.8 | 13.4 | 18 |
| 43 | 18 | 540 | 48.4 | 2892 | 2276 | 221 | 640 | 7.61 | 48.7 | 2.6 | 30 | 51 | 4.8 | 14 | 18 |
| 44 | 19 | 508 | 49.8 | 2804 | 2408 | 235 | 660 | 7.63 | | | | 47 | 5.7 | 20.5 | 18 |
| 45 | 20 | 459 | 51.8 | 2724 | 2342 | 250 | 680 | 7.32 | | | | 59 | 3.2 | 21.9 | 18 |
| 46 | 21 | 528 | 51.5 | 2724 | 2322 | 240 | 660 | 7.3 | 38.7 | 2.8 | 37 | 45 | 2.5 | 30.2 | 18.5 |
| 47 | 22 | 433 | 50.1 | 2750 | 2382 | 247 | 680 | 7.79 | 15.2 | 3.1 | 85.7 | 43 | 2.9 | 35.6 | 19 |
| 48 | 23 | 466 | 48.4 | 2634 | 2238 | 259 | 680 | 7.6 | 33.9 | 2.7 | 42.1 | 43 | 1.4 | 38.8 | 18.5 |
| 49 | 24 | 454 | 47.9 | 2688 | 2302 | 257 | 680 | 7.57 | 43.3 | 2.7 | 32 | 41 | 3.4 | 29.7 | 19 |
| 50 | 25 | 421 | 45.6 | 2718 | 2422 | 247 | 672 | 7.73 | 42.4 | 2.7 | 34 | 41 | 4.2 | 30.5 | 19 |
| 51 | 26 | 586 | 44.8 | 2542 | 2206 | 255 | 648 | 7.54 | | | | 37 | 3.5 | 29.2 | 17.5 |
| 52 | 27 | 574 | 49.8 | 2580 | 2120 | 256 | 660 | 7.72 | | | | 27 | 1.4 | 23.3 | 19 |
| 53 | 28 | 456 | 33.6 | 2798 | 2434 | 247 | 681 | 7.6 | 50.8 | 2.3 | 27.9 | 43 | 2.2 | 17.6 | 20 |
| 54 | 29 | 559 | 34 | 2790 | 2412 | 244 | 681 | 7.56 | 50.7 | 2.3 | 27.1 | 45 | 1.75 | 15 | 19 |
| 55 | 30 | 547 | 45.4 | 2678 | 2312 | 246 | 665 | 7.74 | 55.1 | 2.5 | 27.1 | 41 | 5.3 | 12.3 | 18.5 |
| 56 | 31 | 646 | 47.9 | | | | | | | | | 47 | 5.3 | 13.1 | 19.5 |

Month: June 1990

| | | Influent | | CFR 2 | | | | | | | Effluents | | | Infl. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Day | Date | COD mg/l | TKN mg/l | MLSS mg/l | VSS mg/l | DSVI ml/g | Sett ml/l | pH | OUR mg/l/h | peak | aerob. % | COD mg/l | TKN mg/l | NO3 mg/l | NO3 |
| 57 | 1 | 584 | 41.4 | 2710 | 2396 | 266 | 720 | 7.74 | | | | 43 | 4.3 | 15.3 | 19.5 |
| 58 | 2 | 576 | 51.8 | 2652 | 2322 | 284 | 752 | 7.74 | | | | 43 | 3.2 | 17.5 | 19.5 |
| 59 | 3 | 563 | 48.2 | 2764 | 2416 | 272 | 752 | 7.75 | | | | 52 | 4.1 | 19.3 | 20 |
| 60 | 4 | 539 | 54.3 | 2790 | 2428 | 265 | 740 | 7.68 | | | | 54 | 5.2 | 18.9 | 19.2 |
| 61 | 5 | 551 | 46.8 | 2784 | 2428 | 287 | 800 | 7.62 | 47.4 | 2.5 | 29.3 | 52 | 4.6 | 16.5 | 18.6 |
| 62 | 6 | 572 | 53.9 | 2880 | | 278 | 800 | 7.66 | 50.7 | 2.5 | 28.5 | 58 | 4.7 | 14.3 | 19.75 |
| 63 | 7 | 552 | 48.3 | 3146 | 2742 | 318 | 1000 | 7.73 | 48.6 | 2.3 | 27.9 | 56 | 5.7 | 18.7 | 19.43 |
| 64 | 8 | 531 | 41.7 | 2714 | 2388 | 295 | 800 | 7.61 | | | | | | | 15 |
| 65 | 9 | | | | | | | | | | | 49 | 3.8 | 15.3 | 15 |
| 66 | 10 | 513 | 39 | | | | | | | | | 56 | 5.3 | 7.1 | 15 |
| 67 | 11 | 536 | 52.5 | 2670 | | 292 | 780 | 7.57 | 49.6 | 2.5 | 29.3 | 66 | 6.2 | 15.7 | 21.18 |
| 68 | 12 | 515 | 45.8 | | | | 760 | 7.6 | | | | 33 | 6.2 | 22.1 | 19.11 |
| 69 | 13 | 400 | 40.3 | 2706 | 2402 | 310 | 840 | 7.53 | | | | 43 | 3.5 | 25.2 | 19.5 |
| 70 | 14 | 340 | 39.8 | 2580 | 2234 | 321 | 828 | 7.56 | 27.3 | | | 35 | 3.2 | 28 | 20.45 |
| 71 | 15 | 394 | 40.9 | 2594 | 2244 | 324 | 840 | 7.53 | | | | 31 | 2.5 | 28.9 | 17.14 |
| 72 | 16 | 374 | 40.6 | 2626 | 2284 | 307 | 800 | 7.57 | | | | 35 | 4.5 | 27.5 | 20.24 |
| 73 | 17 | 338 | 49.6 | | | | | | | | | 40 | 3.9 | 26.7 | 20.2 |
| 74 | 18 | 339 | 44.2 | 2792 | 2358 | 304 | 848 | 7.84 | | | | 46 | 4.8 | 24.9 | 7 |
| 75 | 19 | 323 | 44.2 | 2678 | 2276 | 303 | 812 | 7.65 | 37.6 | 2.55 | 37.5 | 42 | 5.3 | 19.3 | 17.14 |
| 76 | 20 | 327 | 43.7 | 2526 | 2224 | 317 | 800 | 7.66 | 43.7 | 2.6 | 26 | 44 | 4.1 | 19.2 | 19.86 |
| 77 | 21 | 314 | 52.4 | 2524 | 2168 | 325 | 820 | 7.66 | 45.7 | 2.6 | 27.6 | 40 | 5.3 | 19.4 | 16.36 |
| 78 | 22 | 347 | 49 | 2508 | 2130 | 319 | 800 | 7.63 | | | | 33 | 2.8 | 14.3 | 18.26 |
| 79 | 23 | 454 | 68.1 | | | | | | | | | 84 | 7.2 | 17 | 18.25 |
| 80 | 24 | 524 | 65.4 | | | | | | | | | 45 | 4.2 | 4.4 | 2.5 |
| 81 | 25 | 446 | 58 | 2752 | 2368 | 317 | 872 | 7.87 | 47.1 | 2.6 | 24.6 | 55 | 5.3 | 1.9 | 16.36 |
| 82 | 26 | 516 | 70.1 | 2513 | 2202 | 350 | 880 | 7.77 | | | | 57 | 4.8 | 6.3 | 16.8 |
| 83 | 27 | 577 | 66.5 | 2696 | 2336 | 334 | 900 | 7.75 | | | | 47 | 3.7 | 20 | 15 |
| 84 | 28 | 390 | 42.9 | 2620 | 2266 | 321 | 840 | 7.73 | 47.4 | 2.5 | 30 | 45 | 4.1 | 19.6 | 18.22 |
| 85 | 29 | 510 | 64.1 | 2752 | 2356 | 327 | 900 | 7.67 | 45.7 | 2.6 | 30.7 | 93 | 7.7 | 25.4 | 17.5 |
| 86 | 30 | 449 | 55.2 | | | | | | | | | 53 | 4.2 | 28.2 | 17.5 |

Month; July 1990

| | | Influent | | CFR 2 | | | | | | | Effluents | | | Infl. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Day | Date | COD mg/l | TKN mg/l | MLSS mg/l | VSS mg/l | DSVI ml/g | Sett ml/l | pH | OUR mg/l/h | peak | aerob. % | COD mg/l | TKN mg/l | NO3 mg/l | NO3 |
| 87 | 1 | 415 | 56.8 | | | | | | | | | 41 | 5.6 | 23.1 | 12.5 |
| 88 | 2 | 358 | 57.7 | 2620 | 2240 | 320 | 840 | 7.56 | 66.8 | 2.7 | 28.2 | | | | |
| 89 | 3 | | | | | | | | | | | 59 | 7.1 | 9.2 | |
| 90 | 4 | | | | | | | | | | | 47 | 7.6 | 19 | |
| 91 | 5 | 380 | 54.6 | | | | | | | | | 41 | 0.7 | 27 | 15.79 |
| 92 | 6 | 384 | 56.6 | 2468 | 2126 | 357 | 880 | 7.6 | 58 | 2.9 | 29.5 | | | | 16.44 |
| 93 | 7 | | | | | | | | | | | 59 | 5.9 | 21.6 | 16.44 |
| 94 | 8 | 510 | 53.2 | | | | | | | | | 55 | 4.5 | 27 | 16.44 |
| 95 | 9 | 599 | 58.2 | 2490 | 2190 | 369 | 920 | 7.59 | 55.4 | 2.5 | 31.2 | 20 | 5.9 | 19.8 | 18.26 |
| 96 | 10 | 404 | 65.8 | 2842 | 2478 | 322 | 916 | 7.73 | 43.2 | 2.4 | 32.2 | | | | 17.5 |
| 97 | 11 | | | | | | | | | | | | | | 17.5 |
| 98 | 12 | | | | | | | | | | | | | | 17.5 |
| 99 | 13 | | | | | | | | | | | | | | 17.5 |
| 100 | 14 | | | | | | | | | | | | | | 17.5 |
| 101 | 15 | | | | | | | | | | | 35 | 2.8 | 29.2 | 17.5 |
| 102 | 16 | 396 | 26 | 2560 | 2234 | 357 | 916 | 7.62 | 52 | 2.7 | 28.3 | 33 | 3.1 | 33.5 | 17.41 |
| 103 | 17 | 534 | 57.4 | 2400 | 2082 | 395 | 950 | 7.44 | 54.2 | 2.4 | 27.9 | | | | 17.5 |
| 104 | 18 | | | | | | | | | | | | | | 17.5 |
| 105 | 19 | | | | | | | | | | | 49 | 8.5 | 31.2 | 17.5 |
| 106 | 20 | 596 | 61.3 | | | | | | | | | 51 | 8.4 | 29.5 | 17.5 |
| 107 | 21 | 628 | 61.3 | 2456 | 2142 | 335 | 825 | 7.81 | 55 | 2.5 | 27.6 | 49 | 9 | 28.5 | 17.14 |
| 108 | 22 | 632 | 59.6 | 2354 | 2032 | 346 | 815 | 7.69 | 37.5 | 2.6 | 35.2 | | | | 18.32 |
| 109 | 23 | | | 2338 | 2028 | 321 | 750 | 7.64 | 43.2 | 2.6 | 33.4 | 53 | 8.7 | 26.2 | 17.21 |
| 110 | 24 | 628 | 61.8 | 2870 | 2488 | 340 | 975 | 7.57 | 48.4 | 2.5 | 32.1 | 53 | 7.7 | 25.4 | 16 |
| 111 | 25 | 477 | 54.6 | 2398 | 2104 | 329 | 158 | | | | | 55 | 10.6 | 17.6 | 17.14 |
| 112 | 26 | 571 | 55.2 | 2312 | 2020 | 346 | 800 | 7.6 | 43 | 2.6 | 33.5 | 57 | 6.3 | 14.9 | 0 |
| 113 | 27 | 612 | 55.7 | 2312 | 2020 | 357 | 825 | 7.5 | | | | | | | 7.61 |
| 114 | 28 | 426 | | | | | | | | | | 43 | 6.2 | 17.4 | 7.61 |
| 115 | 29 | 512 | 36 | | | | | | | | | 43 | 5.7 | 14.9 | 7.61 |
| 116 | 30 | 504 | 55.7 | 2202 | 1900 | 375 | 825 | 7.68 | 31.5 | 2.5 | 40 | 45 | 5.5 | 20 | 16.37 |
| 117 | 31 | 406 | 52.6 | 2112 | 1858 | 398 | 840 | 7.58 | 32.1 | 2.7 | 42 | 49 | 5.9 | 28.9 | 18.95 |

Month; August 1990

| | | Influent | | CFR 2 | | | | | | | | Effluents | | | Infl. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Day | Date | COD mg/l | TKN mg/l | MLSS mg/l | VSS mg/l | DSVI ml/g | Sett ml/l | pH | OUR mg/l/h | peak | aerob. % | COD mg/l | TKN mg/l | NO3 mg/l | NO3 |
| 118 | 1 | 451 | 52.9 | 1934 | 1622 | 400 | 775 | 7.48 | | 2 | 100 | 30 | 3.9 | 35.3 | |
| 119 | 2 | 508 | 56 | 1964 | 1694 | 420 | 825 | 7.32 | 29.1 | 2 | 100 | 51 | 2.9 | 35.8 | |
| 120 | 3 | 569 | 62.6 | 1996 | 1738 | 425 | 850 | 7.68 | | 2 | 100 | | | | |
| 121 | 4 | | | | | | | | | 2 | 100 | 51 | 2.7 | 42.9 | |
| 122 | 5 | 514 | 63.6 | | | | | | 21.3 | 2 | 100 | 45 | 3.4 | 45 | |
| 123 | 6 | 538 | 40 | 2466 | 2156 | 314 | 775 | 7.4 | 24.7 | 2 | 100 | 57 | 2.4 | 47 | |
| 124 | 7 | 541 | 66.1 | 2746 | 2366 | 191 | 525 | 7.42 | 26.5 | 2 | 100 | 55 | 3.8 | 50 | |
| 125 | 8 | 545 | 63.6 | 2530 | 2196 | 134 | 425 | 7.3 | 26.2 | 2 | 100 | 61 | 6.2 | 49 | |
| 126 | 9 | 500 | 63 | 2452 | 2130 | 139 | 340 | 7.43 | 24.2 | 2 | 100 | 57 | 5 | 49 | |
| 127 | 10 | 395 | 39.5 | 2352 | 2072 | 122 | 288 | 7.41 | | 5.8 | 100 | | | | |
| 128 | 11 | | | | | | | | | 5.8 | 100 | 49 | 3.2 | 39.7 | |
| 129 | 12 | 393 | 41.2 | | | | | | 25.2 | 5.8 | 100 | 57 | 3.8 | 32.6 | |
| 130 | 13 | 415 | 41.4 | 2384 | 2026 | 130 | 310 | 7.57 | 15.4 | 2.3 | 30 | 39 | 7 | 24.2 | 16.57 |
| 131 | 14 | 407 | 41.2 | 2498 | 2150 | 133 | 333 | 7.67 | 23.7 | 2.3 | 30 | 52 | 3.8 | 25.6 | 21.06 |
| 132 | 15 | 491 | 46.8 | 2342 | 2012 | 142 | 333 | 7.55 | 17 | 2.3 | 30 | 38 | 9 | 34.1 | 25 |
| 133 | 16 | 503 | 46.8 | 2290 | 1964 | 134 | 307 | 7.52 | 17.5 | 2.3 | 30 | 40 | 9.8 | 25.5 | 20.35 |
| 134 | 17 | 515 | 41.4 | 2196 | 1864 | 142 | 311 | 7.8 | | 2.3 | 30 | 42 | | 18.4 | 17.14 |
| 135 | 18 | 503 | 46.2 | | | | | | | 2.3 | 30 | 38 | 9.7 | 15 | 17.14 |
| 136 | 19 | 435 | 51.5 | | | | | | 28.3 | 2.3 | 30 | 56 | | 11.5 | 19.76 |
| 137 | 20 | 469 | 47.3 | 2414 | 2122 | 129 | 311 | 7.84 | 31.7 | 2.3 | 30 | 54 | 5.8 | 12.6 | 17.45 |
| 138 | 21 | 459 | 46.9 | 2028 | 1748 | 153 | 311 | 7.63 | 29.1 | 2.3 | 30 | 48 | 6.2 | 9.4 | 18.46 |
| 139 | 22 | 435 | 46.1 | 2274 | 1960 | 140 | 318 | 7.73 | 28.1 | 2.3 | 30 | 29 | 5.4 | 12.1 | 20 |
| 140 | 23 | 448 | 38.5 | 2210 | 1938 | 140 | 311 | 7.69 | 30 | 2.3 | 30 | 35 | 3.5 | 15.5 | 19.64 |
| 141 | 24 | 473 | 40.3 | 2320 | 1974 | 144 | 333 | 7.77 | | 2.3 | 30 | 39 | 2.7 | 12.3 | 22.3 |
| 142 | 25 | 473 | 39.5 | | | | | | 28.5 | 2.3 | 30 | 41 | 3.95 | 14.8 | 22.5 |
| 143 | 26 | 469 | 40.2 | | | | | | 31.1 | 2.3 | 30 | 47 | 6.9 | 17 | 21.18 |
| 144 | 27 | 415 | 38 | 2262 | 1944 | 138 | 311 | 7.8 | 33 | 2.3 | 30 | 47 | 7.2 | 22.4 | 21.78 |
| 145 | 28 | 476 | 33.6 | 2194 | 1944 | 145 | 318 | 7.62 | 31.9 | 2.3 | 30 | 47 | 4.1 | 20.9 | 18.75 |
| 146 | 29 | 557 | 31.9 | 2136 | 1838 | 149 | 318 | 7.63 | 34.7 | 2.3 | 30 | 51 | 5.6 | 20.2 | 20.4 |
| 147 | 30 | 520 | 56.6 | 2178 | 2082 | 146 | 318 | 7.65 | 36.9 | 2.3 | 30 | 46 | 4.3 | 28.4 | 21.92 |
| 148 | 31 | 450 | 44.9 | | | | | | 36 | 2.3 | 30 | 54 | 0.3 | 27.1 | 21.9 |

Month: October 1990

| | | Influent | | CFR 2 | | | | | | | | Effluents | | | Infl. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Day | Date | COD mg/l | TKN mg/l | MLSS mg/l | VSS mg/l | DSVI ml/g | Sett ml/l | pH | OUR mg/l/h | peak | aerob. % | COD mg/l | TKN mg/l | NO3 mg/l | NO3 |
| 179 | 1 | 550 | 34.2 | 2044 | 1748 | 391 | 800 | 7.72 | 23.6 | 2.3 | 30 | 43 | 0 | 5.8 | |
| 180 | 2 | 411 | 36.1 | 2080 | 1808 | 352 | 732 | 7.7 | | 2.3 | 30 | 47 | 1.4 | 5.3 | |
| 181 | 3 | 429 | 22.7 | 1810 | 1550 | 404 | 732 | 7.63 | 19.8 | 2.3 | 30 | | | | |
| 182 | 4 | | | 1862 | 1590 | 408 | 760 | 7.69 | 19.7 | 2.3 | 100 | 49 | 1.8 | 5.8 | |
| 183 | 5 | 551 | 42.5 | | | | | | 22 | 2.3 | 100 | 69 | 0.4 | 14.1 | |
| 184 | 6 | 466 | 36.5 | | | | | | 20.6 | 2.3 | 100 | 49 | 2.4 | 28.8 | |
| 185 | 7 | 488 | 37.2 | | | | | | 23.1 | 2.3 | 100 | 49 | 2.8 | 33.8 | |
| 186 | 8 | 472 | 38.1 | 2272 | 1972 | 290 | 660 | 7.58 | | 2.3 | 100 | 46 | 0 | 35.1 | |
| 187 | 9 | 503 | 37.8 | 2590 | 2210 | 286 | 740 | 7.53 | 22.7 | 2.3 | 100 | 50 | 2.6 | 38.3 | |
| 188 | 10 | 445 | 37.1 | 2846 | 2460 | 201 | 572 | 7.51 | 23.4 | 2.3 | 100 | 50 | 2.6 | 41.3 | |
| 189 | 11 | 425 | 36.7 | | | | | | 24.5 | 2.3 | 100 | 54 | 1.7 | 45.1 | |
| 190 | 12 | 505 | 51.6 | 2654 | 2264 | 121 | 320 | 7.41 | | 2.3 | 100 | 54 | 1.4 | 44.5 | |
| 191 | 13 | 518 | 51.8 | | | | | | 27.1 | 2.3 | 100 | 66 | 1.7 | 45.6 | |
| 192 | 14 | 457 | 49.6 | | | | | | 23.8 | 2.3 | 100 | 64 | 1.3 | 45.1 | |
| 193 | 15 | 513 | 47.6 | 2350 | 2004 | 130 | 304 | 7.45 | 19.9 | 2.3 | 90 | 50 | 1.5 | 44.5 | 24 |
| 194 | 16 | 603 | 51.5 | 2292 | 1958 | 136 | 311 | 7.62 | | | 0 | 44 | 12 | 32.9 | 22.5 |
| 195 | 17 | 566 | 50.5 | | | | | | | | 0 | | 9.4 | 19 | 24 |
| 196 | 18 | | | 2262 | 1936 | 150 | 340 | 7.74 | 23.1 | 2.3 | 90 | 64 | 12.1 | 28.4 | 23.5 |
| 197 | 19 | 574 | 45.9 | 2270 | 1934 | 147 | 333 | 7.49 | | | 0 | 42 | 12.9 | 17 | 22.5 |
| 198 | 20 | 485 | 52.2 | | | | | | | | 0 | 77 | 27 | 3.1 | 22.5 |
| 199 | 21 | 501 | 49.5 | | | | | | 34.3 | 2.3 | 90 | 49 | 3.5 | 32.2 | 22.5 |
| 200 | 22 | 537 | 47.7 | 2282 | 1954 | 154 | 351 | 7.7 | | | 0 | 59 | 12.1 | 3.7 | 20 |
| 201 | 23 | 426 | 49.3 | 2270 | 1946 | 150 | 340 | 7.69 | | | 0 | 73 | 21.9 | 0.2 | 20 |
| 202 | 24 | 499 | 47.4 | 2262 | 1938 | 157 | 356 | 7.7 | 24.9 | 2.3 | 90 | 73 | 17.2 | 10.9 | 19.64 |
| 203 | 25 | 596 | 50.3 | 2172 | 1862 | 159 | 344 | 7.59 | | | 0 | 53 | 11.2 | 11.1 | 18.95 |
| 204 | 26 | 572 | 52 | 2220 | 1916 | 160 | 356 | 7.61 | | | 0 | 65 | 25.6 | 0.3 | 17.65 |
| 205 | 27 | 485 | 37 | | | | | | 31.7 | 2.3 | 90 | 52 | 2.3 | 32.9 | 17.65 |
| 206 | 28 | 540 | 47.3 | | | | | | | | 0 | 52 | 1.7 | 17.6 | 17.65 |
| 207 | 29 | 455 | 51 | 2456 | 1832 | 163 | 400 | 7.72 | | | 0 | 84 | 30.9 | 0.3 | 16.7 |
| 208 | 30 | 520 | 51.6 | 2338 | 2014 | 197 | 460 | 7.83 | 23.4 | 2.3 | 90 | 64 | 12.1 | 28.42 | 19.5 |
| 209 | 31 | 561 | 51.8 | 2298 | 1988 | 179 | 412 | 7.54 | | | 0 | 64 | 11.5 | 12.5 | 24 |

Month; November 1990

| | | Influent | | CFR 2 | | | | | | | Effluents | | | Infl. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Day | Date | COD mg/l | TKN mg/l | MLSS mg/l | VSS mg/l | DSVI ml/g | Sett ml/l | pH | OUR mg/l/h | peak | aerob. % | COD mg/l | TKN mg/l | NO3 mg/l | NO3 |
| 210 | 1 | 557 | 54.6 | 2268 | 1966 | 203 | 460 | 7.62 | | | 0 | 84 | 24.5 | 0 | 6.764 |
| 211 | 2 | 536 | 54.6 | 2124 | 1834 | 245 | 520 | 7.58 | 24 | 2.3 | 100 | 61 | 11.1 | 27.6 | 13.09 |
| 212 | 3 | 523 | 58 | | | | | | | | 0 | 51 | 0.9 | 33.2 | 5.793 |
| 213 | 4 | 479 | 54.5 | | | | | | | | 0 | 57 | 1.9 | 21.2 | 5.8 |
| 214 | 5 | 529 | 50.2 | 2116 | 1834 | 227 | 480 | 7.64 | 27.4 | 2.3 | 100 | 61 | 2 | 22.6 | 9.778 |
| 215 | 6 | 535 | 50.7 | 2408 | 2088 | 199 | 480 | 7.63 | | | 0 | 357 | 9.4 | 25.2 | 15.71 |
| 216 | 7 | 633 | 56.5 | 2192 | 1890 | 210 | 460 | 7.7 | | | 0 | 65 | 26.3 | 0 | 11.83 |
| 217 | 8 | 608 | 103 | 2198 | 1926 | 227 | 500 | 7.7 | | | 0 | 136 | 41.6 | 5.5 | 11.45 |
| 218 | 9 | 389 | 59.8 | 2238 | 1924 | 263 | 588 | 7.85 | | | 0 | 105 | 44.7 | 3.2 | 9 |
| 219 | 10 | 479 | 81.7 | | | | | | | | 0 | 116 | 43.3 | 0 | 9 |
| 220 | 11 | 629 | 96.5 | 2002 | 1726 | 300 | 600 | 7.82 | | | 0 | 150 | 60.2 | 3.3 | 22.5 |
| 221 | 12 | 665 | 104 | | | | | | | | 0 | 148 | 71.9 | 77.7 | 192 |
| 222 | 13 | 657 | 97.6 | 2194 | 1884 | 210 | 460 | 7.9 | | | 0 | 142 | 65.3 | 86.5 | 132.9 |
| 223 | 14 | | | 2086 | 1752 | 182 | 380 | 7.93 | | | 0 | | | | 120.9 |
| 224 | 15 | 462 | 52.5 | 1976 | 1668 | 162 | 320 | 7.95 | | | 0 | 127 | 51.3 | 86.5 | 124.8 |
| 225 | 16 | 507 | 49.5 | 1894 | 1628 | 152 | 288 | 7.81 | | | 0 | 70 | 27.4 | 55.2 | 84.21 |
| 226 | 17 | 543 | 41.9 | | | | | | | | 0 | 78 | 309 | 48.4 | 84.2 |
| 227 | 18 | 517 | 38.6 | | | | | | | | 0 | 94 | 30.8 | 48.4 | 173.3 |
| 228 | 19 | 531 | 39.9 | 1768 | 1532 | 145 | 256 | 7.75 | | | 0 | 70 | 20.3 | 50.3 | 160 |
| 229 | 20 | 513 | 33.9 | 1866 | 1588 | 143 | 267 | 7.7 | | | 0 | 78 | 21.8 | 68 | 120 |
| 230 | 21 | 527 | 34.9 | 1964 | 1694 | 130 | 256 | | | | 0 | 94 | 20.8 | 71 | 111.3 |
| 231 | 22 | 539 | 41.1 | 1906 | 1586 | 140 | 269 | 7.82 | | | 0 | 76 | 21.9 | 47.5 | 112 |
| 232 | 23 | 560 | 35.5 | 1958 | 1720 | 142 | 278 | 7.8 | | | 0 | 70 | 21.7 | 43.8 | 80 |
| 233 | 24 | 562 | 42.6 | | | | | | | | 0 | 74 | 21.5 | 83.8 | 192 |
| 234 | 25 | | 43.9 | 2050 | 1694 | 137 | 280 | 8 | | | 0 | 92 | 18.7 | 71 | 126 |
| 235 | 26 | 722 | 39.7 | 2146 | 1806 | 130 | 280 | 7.9 | | | 0 | 133 | 26.7 | 65 | 110.4 |
| 236 | 27 | 566 | 42.3 | 1980 | 1696 | 136 | 273 | 8 | | | 0 | 122 | 26.8 | 27.2 | 107.1 |
| 237 | 28 | 572 | 42.4 | 1882 | 1588 | 136 | 256 | 7.78 | | | 0 | 91 | 25.6 | 50.3 | 98 |
| 238 | 29 | 542 | 39.9 | 1960 | 1676 | 119 | 233 | 7.88 | | | 0 | 87 | 24.9 | 35.6 | 98 |
| 239 | 30 | 502 | 40.2 | 2268 | 1914 | 108 | 244 | 7.81 | | | 0 | 83 | 25.5 | 42.6 | 97.96 |
| | | December 1990 | | | | | | | | | | | | | |
| 240 | 1 | 498 | 39.7 | | | | | | | | 0 | 89 | 26.1 | 68 | 98 |
| 241 | 2 | | | 2218 | 1736 | 105 | 233 | 7.8 | | | 0 | | 26.7 | 36 | |

Month: April 1990

| | | Influent | | CFR 3 | | | | | | | | Effluents | | | Infl. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Day | Date | COD mg/l | TKN mg/l | MLSS mg/l | VSS mg/l | DSVI ml/g | Sett ml/l | pH | OUR | peak | aerob. % | COD mg/l | TKN mg/l | NO3 mg/l | NO3 mg/l |
| | 1 | | | | | | | | | | | | | | |
| | 2 | | | | | | | | | | | | | | |
| | 3 | | | | | | | | | | | | | | |
| | 4 | | | | | | | | | | | | | | |
| 0 | 5 | 466 | 45.4 | | | | | | | | | 68 | 15.4 | 0 | |
| 1 | 6 | 470 | 44.8 | 4990 | | 176 | 880 | 7.55 | | | | 48 | 14.6 | 0 | |
| 2 | 7 | 470 | 45.1 | 3864 | | 217 | 840 | 7.75 | | | | 52 | 4.2 | 35.9 | 25 |
| 3 | 8 | 493 | 42.6 | | | | | | | | | 36 | 4.2 | 55.3 | 25 |
| 4 | 9 | 460 | 44 | 4160 | | 197 | 820 | 7.4 | 49 | 2.4 | 33 | 27 | 2.8 | 54.1 | 44.44 |
| 5 | 10 | 477 | 39.2 | 3828 | | 219 | 840 | 7.4 | 35 | 2.7 | 54 | 38 | 0.7 | | 17.87 |
| 6 | 11 | 434 | 36.1 | 3762 | 3308 | 207 | 780 | 7.3 | 20 | 2.6 | 56.5 | 21 | 5 | | 38.5 |
| 7 | 12 | 472 | 37.2 | 3002 | 2628 | 227 | 680 | 7.6 | 37.3 | 1.9 | 25 | 38 | 1.54 | 64.9 | 25.53 |
| 8 | 13 | 598 | 47 | | | | | | | | | 42 | 4.3 | 64.1 | 25.5 |
| 9 | 14 | 533 | 45.9 | | | | | | | | | 42 | 2.8 | 51.1 | 31 |
| 10 | 15 | 586 | 52.1 | 3186 | 2824 | 220 | 700 | 7.65 | | | | 46 | 5.5 | 49.6 | 30 |
| 11 | 16 | 631 | 52.1 | 2864 | 2510 | 251 | 720 | 7.55 | 54.7 | 2.9 | 29 | 38 | 1.4 | 40.8 | 20.87 |
| 12 | 17 | 663 | 53.5 | 3156 | 2782 | 228 | 720 | 7.5 | 47.4 | 2.8 | 28 | 43 | 5.9 | 34.8 | 21.27 |
| 13 | 18 | 567 | 52.6 | 3108 | 2674 | 228 | 710 | 7.6 | 51.5 | 2.9 | 28 | 49 | 4.6 | 34.8 | 19 |
| 14 | 19 | 614 | 55.2 | 3646 | 2802 | 203 | 740 | 7.6 | 52.1 | 2.5 | 29.3 | 53 | 9.8 | 30 | 22.56 |
| 15 | 20 | 471 | 46.5 | 2868 | 2504 | 244 | 700 | 7.6 | 52.4 | 2.55 | 25.3 | 65 | 4.5 | 20.1 | 17.5 |
| 16 | 21 | 508 | 45.9 | | | | | | | | | 47 | 5.2 | 24.6 | 15 |
| 17 | 22 | 504 | | | | | | | | | | 32 | 2.1 | 25.7 | 15 |
| 18 | 23 | 462 | 46.5 | 2960 | 2626 | 223 | 660 | 7.4 | 47.4 | 2.55 | 29.6 | 41 | 2.5 | 24.4 | 25.26 |
| 19 | 24 | 539 | 42.4 | 2736 | 2420 | 256 | 700 | 7.6 | 58.9 | 2.6 | 25 | 45 | 3.2 | 21.2 | 25.33 |
| 20 | 25 | 470 | 40.5 | 2976 | 2608 | 242 | 720 | 7.6 | | | | 49 | 3.2 | 21.2 | 15.84 |
| 21 | 26 | 462 | 40.5 | 2540 | 2410 | 268 | 680 | 7.55 | 46.8 | 2.6 | 30.7 | 49 | 1.6 | 23.4 | 16.36 |
| 22 | 27 | 487 | 43.1 | 2872 | 2548 | 230 | 660 | 7.65 | 48.5 | 2.6 | 29.3 | 49 | 4.4 | 16.5 | 16 |
| 23 | 28 | 475 | 39.4 | | | | | | | | | 49 | 1.8 | 23.4 | 16 |
| 24 | 29 | 564 | 44.2 | | | | | | | | | 57 | 2.4 | 24.9 | 16 |
| 25 | 30 | 540 | 46.1 | 2592 | 2250 | 262 | 680 | 7.65 | 51.9 | 2.5 | 26.4 | 53 | 4.3 | 21.6 | 10 |

Month; July 1990

| | | Influent | | CFR 3 | | | | | | | Effluents | | | Infl. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Day | Date | COD mg/l | TKN mg/l | MLSS mg/l | VSS mg/l | DSVI ml/g | Satt ml/l | pH | OUR | peak DO | Aerob. % | COD mg/l | TKN mg/l | NO3 mg/l | NO3 mg/l |
| 87 | 1 | 415 | 56.8 | | | | | | | | | 57 | 7.4 | 10 | 5.6 |
| 88 | 2 | 358 | 57.7 | 2582 | 2214 | 387 | 1000 | 7.61 | 50.5 | 2.4 | 30 | | | | 5 |
| 89 | 3 | | | | | | | | | | | 51 | 7.6 | 10.3 | |
| 90 | 4 | | | | | | | | | | | 39 | 7.6 | 12 | |
| 91 | 5 | 380 | 54.6 | | | | | | | | | 63 | 7 | 10.8 | 5.06 |
| 92 | 6 | 384 | 56.6 | 2550 | 2220 | 373 | 952 | 7.84 | 48.2 | 2.4 | 30 | | | | 5.9 |
| 93 | 7 | | | | | | | | | | | 63 | 6.3 | 10.5 | 5.9 |
| 94 | 8 | 510 | 53.2 | | | | | | | | | 63 | 8.1 | 9.7 | 5.9 |
| 95 | 9 | 599 | 58.2 | 2400 | 2108 | 383 | 920 | 7.8 | 45.2 | 2.4 | 30 | 49 | 6.7 | 12.5 | 11 |
| 96 | 10 | 404 | 65.8 | 2724 | 2402 | 330 | 900 | 7.59 | 52.3 | 2.4 | 30 | | | | 6 |
| 97 | 11 | | | | | | | | | | | | | | 6 |
| 98 | 12 | | | | | | | | | | | | | | 6 |
| 99 | 13 | | | | | | | | | | | | | | 6 |
| 100 | 14 | | | | | | | | | | | | | | 6 |
| 101 | 15 | | | | | | | | | | | 61 | 6.3 | 13.6 | 6 |
| 102 | 16 | 396 | 26 | 2308 | 2080 | 368 | 852 | 7.52 | 40.2 | 2.4 | 30 | 49 | 6.6 | 21.4 | 6.024 |
| 103 | 17 | 534 | 57.4 | 2200 | 1938 | 420 | 925 | 7.47 | 35.2 | 2.4 | 30 | | | | 6 |
| 104 | 18 | | | | | | | | | | | | | | 6 |
| 105 | 19 | | | | | | | | | | | 61 | 7.3 | 21.9 | 6 |
| 106 | 20 | 596 | 61.3 | | | | | | | | | 57 | 7.8 | 17.7 | 6 |
| 107 | 21 | 628 | 61.3 | 2560 | 2242 | 352 | 900 | 7.8 | 42.5 | 2.4 | 30 | 53 | 8.1 | 16.7 | 9.6 |
| 108 | 22 | 632 | 59.6 | 2564 | 2292 | 337 | 865 | 7.77 | 43.2 | 2.4 | 30 | | | | 7.074 |
| 109 | 23 | | | 2768 | 2414 | 303 | 840 | 7.63 | 55.1 | 2.4 | 30 | 57 | 7.8 | 19.2 | 5.253 |
| 110 | 24 | 628 | 61.8 | 2632 | 2332 | 323 | 850 | 7.74 | 49.7 | 2.4 | 30 | 41 | 8 | 14.1 | 7.6 |
| 111 | 25 | 477 | 54.6 | 2702 | 2360 | 311 | 840 | | | | | 57 | 7.1 | 13.9 | 9.326 |
| 112 | 26 | 571 | 55.2 | 2462 | 2208 | 335 | 825 | 7.58 | 47.4 | 2.4 | 30 | 49 | 7.3 | 13.8 | 5.486 |
| 113 | 27 | 612 | 55.7 | 2494 | 2196 | 321 | 800 | 7.56 | | | | | | | 5.854 |
| 114 | 28 | 426 | | | | | | | | | | 63 | 6.6 | 14.9 | 5.854 |
| 115 | 29 | 512 | 56 | | | | | | | | | 45 | 7.3 | 13.2 | 5.854 |
| 116 | 30 | 504 | 55.7 | 2474 | 2186 | 344 | 850 | 7.73 | | | | 47 | 6 | 16.7 | 7.314 |
| 117 | 31 | 406 | 52.6 | 2686 | 2402 | 335 | 900 | 7.7 | 41.4 | 2.4 | 30 | 63 | 7.1 | 19.1 | 7.326 |

Month: August 1990

| | | Influent | | CFR 3 | | | | | | | | Effluents | | | Infl. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Day | Date | COD mg/l | TKN mg/l | MLSS mg/l | VSS mg/l | DSVI ml/g | Sett ml/l | pH | OUR | peak DO | Aerob. % | COD mg/l | TKN mg/l | NO3 mg/l | NO3 mg/l |
| 118 | 1 | 451 | 52.9 | 2618 | 2208 | 315 | 825 | 7.66 | 35.6 | 2.2 | 30 | 45 | 5.3 | 23.7 | 6.698 |
| 119 | 2 | 508 | 56 | 2496 | 2172 | 357 | 890 | 7.44 | 25.2 | 2.3 | 30 | 55 | 12.3 | 18.7 | 8.139 |
| 120 | 3 | 569 | 62.6 | 2338 | 2062 | 391 | 732 | 7.78 | 45.3 | 2.3 | 30 | | | | 8.388 |
| 121 | 4 | | | | | | | | | 2.3 | 30 | 49 | 11.5 | 18.9 | 8.388 |
| 122 | 5 | 514 | 63.6 | | | | | | | 2.3 | 30 | 61 | 15 | 14.2 | 9.29 |
| 123 | 6 | 538 | 40 | 2514 | 2218 | 388 | 780 | 7.77 | 49 | 2.3 | 30 | 55 | 14.6 | 16.1 | 8.276 |
| 124 | 7 | 541 | 66.1 | 2606 | 2282 | 384 | 1000 | 7.68 | 43 | 2.3 | 30 | 55 | 13.3 | 17.9 | 5.333 |
| 125 | 8 | 545 | 63.6 | 2588 | 2254 | 377 | 975 | 7.75 | 47 | 2.3 | 30 | 55 | 11.5 | 18.5 | 8.914 |
| 126 | 9 | 500 | 63 | 2606 | 2294 | 355 | 925 | 7.78 | 50 | 2.3 | 30 | 61 | 13.2 | 16.9 | 7.2 |
| 127 | 10 | 395 | 39.5 | 2622 | 2330 | 381 | 1000 | 7.68 | 45 | 2.3 | 30 | | | | 5.419 |
| 128 | 11 | | | | | | | | | 2.3 | 30 | 41 | 11.8 | 11.9 | 5.419 |
| 129 | 12 | 393 | 41.2 | | | | | | | 2.3 | 30 | 43 | 8.1 | 6.9 | 5.419 |
| 130 | 13 | 415 | 41.4 | 2522 | 2188 | 373 | 940 | 7.68 | 45.5 | 2.3 | 30 | 51 | 7.7 | 7.8 | 4.2 |
| 131 | 14 | 407 | 41.2 | 2502 | 2182 | 350 | 875 | 7.66 | 43.1 | 2.3 | 30 | 44 | 7.1 | 10 | 10.38 |
| 132 | 15 | 491 | 46.8 | 2542 | 2250 | 364 | 925 | 7.7 | 54.5 | 2.3 | 30 | 44 | 9.1 | 7.7 | 3.4 |
| 133 | 16 | 503 | 46.8 | 2516 | 2184 | 378 | 950 | 7.75 | 26.4 | 4 | 100 | 44 | 3.1 | 25.3 | 0 |
| 134 | 17 | 515 | 41.4 | 2576 | 2222 | 378 | 975 | 7.69 | 20.8 | 4 | 100 | 32 | 2.5 | 32.1 | 0 |
| 135 | 18 | 503 | 46.2 | | | | | | | 4 | 100 | 36 | 2.2 | 34.8 | 0 |
| 136 | 19 | 435 | 51.5 | | | | | | | 4 | 100 | 32 | 2.5 | 32.9 | 0 |
| 137 | 20 | 469 | 47.3 | 3006 | 2616 | 274 | 825 | 7.77 | 24.4 | 2.3 | 30 | 44 | | 28.4 | 8.727 |
| 138 | 21 | 459 | 46.9 | 2542 | 2172 | 364 | 925 | 7.68 | 19.7 | 2.3 | 30 | 50 | 6.2 | 12.9 | 7.385 |
| 139 | 22 | 435 | 46.1 | 2780 | 2412 | 333 | 925 | 7.63 | 28 | 2.3 | 30 | 44 | 4.9 | 13.4 | 6.4 |
| 140 | 23 | 448 | 38.5 | 2638 | 2302 | 354 | 935 | 7.65 | 35 | 2.3 | 30 | 165 | 3.1 | 15.5 | 5.891 |
| 141 | 24 | 473 | 40.3 | 2748 | 2348 | 346 | 950 | 7.75 | 34.6 | 2.3 | 30 | 44 | 4.07 | 17.4 | 3.5 |
| 142 | 25 | 473 | 39.5 | | | | | | | 2.3 | 30 | 50 | 6.4 | 14 | 3.5 |
| 143 | 26 | 469 | 40.2 | | | | | | | 2.3 | 30 | 43 | 7.6 | 10.3 | 2.824 |
| 144 | 27 | 415 | 38 | 2356 | 2032 | 399 | 940 | 7.8 | 51 | 2.3 | 30 | 45 | 6.4 | 16.7 | 14.22 |
| 145 | 28 | 476 | 33.6 | 2520 | 2200 | 397 | 1000 | 7.58 | 45 | 2.3 | 30 | 47 | 5.37 | 16.3 | 6 |
| 146 | 29 | 557 | 31.9 | 2402 | 2076 | 416 | 1000 | 7.62 | 42 | 2.3 | 30 | 51 | 7.44 | 15.3 | 5.76 |
| 147 | 30 | 520 | 56.6 | 2792 | 2400 | 412 | 1150 | 7.6 | 38 | 2.3 | 30 | 48 | 3.7 | 22.9 | 6.234 |
| 148 | 31 | 450 | 44.9 | | | | | | | | | 46 | 5.4 | 19.3 | 6.24 |

Month; October 1990

| | | Influent | | CFR 3 | | | | | | | | Effluents | | | Infl. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Day | Date | COD mg/l | TKN mg/l | MLSS mg/l | VSS mg/l | DSVI ml/g | Sett ml/l | pH | OUR | peak DO | Aerob. % | COD mg/l | TKN mg/l | NO3 mg/l | NO3 mg/l |
| 179 | 1 | 550 | 34.2 | 2324 | 1990 | 258 | 600 | 7.78 | | 2.3 | 30 | 49 | 5.6 | 22.4 | 3.9 |
| 180 | 2 | 411 | 36.1 | 2574 | 2240 | 238 | 612 | 7.76 | 25.8 | 2.3 | 30 | 45 | 3.7 | 19.6 | 10.6 |
| 181 | 3 | 429 | 22.7 | 2350 | 2036 | 272 | 640 | 7.64 | | 2.3 | 30 | | | | 7.68 |
| 182 | 4 | | | 2312 | 1988 | 285 | 660 | 7.66 | 23.4 | 2.3 | 30 | 47 | 2.2 | 20.1 | |
| 183 | 5 | 551 | 42.5 | | | | | | | 2.3 | 30 | 40 | 1.4 | 17 | |
| 184 | 6 | 466 | 36.5 | | | | | | | 2.3 | 30 | 53 | 4.2 | 17 | 5.046 |
| 185 | 7 | 488 | 37.2 | | | | | | | 2.3 | 30 | 27 | 4.7 | 16.3 | 5.04 |
| 186 | 8 | 472 | 38.1 | 2530 | 2204 | 261 | 660 | 7.65 | 21 | 2.3 | 30 | 42 | 4.8 | 17 | 9.135 |
| 187 | 9 | 503 | 37.8 | 2396 | 2064 | 272 | 652 | 7.61 | 23.8 | 2.3 | 30 | 46 | 4.2 | 15 | 8 |
| 188 | 10 | 445 | 37.1 | 2450 | 2112 | 274 | 672 | 7.59 | | 2.3 | 30 | 50 | 3.5 | 16 | 9.183 |
| 189 | 11 | 425 | 36.7 | 2458 | 2126 | 290 | 712 | 7.65 | 24.5 | 2.3 | 30 | 50 | 7.7 | 16 | 12 |
| 190 | 12 | 505 | 51.6 | 2598 | 2240 | 285 | 185 | 7.6 | | 2.3 | 30 | 89 | 5.6 | 17 | 6.588 |
| 191 | 13 | 518 | 51.8 | | | | | | | 2.3 | 30 | 50 | 7.8 | 14.1 | 6.58 |
| 192 | 14 | 457 | 49.6 | | | | | | | 2.3 | 30 | 40 | 8.1 | 11 | 9 |
| 193 | 15 | 513 | 47.6 | 2546 | 2186 | 299 | 760 | 7.65 | 27.6 | 2.3 | 30 | 34 | 7.2 | 17 | 10.88 |
| 194 | 16 | 603 | 51.5 | 2688 | 2308 | 275 | 740 | 7.7 | | 2.3 | 30 | 34 | 14.9 | 17 | 7.2 |
| 195 | 17 | 566 | 50.5 | | | | | | | 2.3 | 30 | | 4.3 | 45.1 | 8 |
| 196 | 18 | | | 2838 | 2476 | 310 | 880 | 7.59 | 22.4 | 2.3 | 30 | 44 | 5.8 | 14.1 | 7.4 |
| 197 | 19 | 574 | 45.9 | 2802 | 2406 | 300 | 840 | 7.57 | 29.6 | 2.3 | 30 | 38 | 2.9 | 13.8 | 7.4 |
| 198 | 20 | 485 | 52.2 | | | | | | | 2.3 | 30 | 56 | 15.6 | 10.4 | 7.4 |
| 199 | 21 | 501 | 49.5 | | | | | | | 2.3 | 30 | 51 | 16.3 | 3.4 | 7.4 |
| 200 | 22 | 537 | 47.7 | 2720 | 2348 | 321 | 872 | 7.6 | 23.2 | 2.3 | 90 | 43 | 3 | 28.2 | 7.36 |
| 201 | 23 | 426 | 49.3 | 3104 | 2678 | 274 | 852 | 7.6 | | | 0 | 45 | 3.4 | 9.9 | 12.8 |
| 202 | 24 | 499 | 47.4 | 2820 | 2434 | 277 | 780 | 7.65 | | | 0 | 47 | 5.3 | 3.3 | 10.18 |
| 203 | 25 | 596 | 50.3 | 2602 | 2242 | 307 | 800 | 7.52 | 25.1 | 2.3 | 90 | 47 | 4.9 | 33.3 | 8.842 |
| 204 | 26 | 572 | 52 | 2540 | 2202 | 307 | 780 | 7.55 | | | 0 | 57 | 14.2 | 5.2 | 7.059 |
| 205 | 27 | 485 | 37 | | | | | | | | 0 | 66 | 7.1 | 33.3 | 7.06 |
| 206 | 28 | 540 | 47.3 | | | | | | 24.1 | 2.3 | 90 | 44 | 1.6 | 30.6 | 7.06 |
| 207 | 29 | 455 | 51 | 2412 | 2322 | 315 | 760 | 7.81 | | | 0 | 46 | 10 | 5.2 | 5.891 |
| 208 | 30 | 520 | 51.6 | 2542 | 2204 | 343 | 872 | 7.79 | | | 0 | 80 | 20.9 | 0.5 | 8.8 |
| 209 | 31 | 561 | 51.8 | 2392 | 2094 | 343 | 820 | 7.64 | 34.8 | 2.3 | 90 | 44 | 11.3 | 35.6 | 9.6 |

Month; November 1990

| | | Influent | | CFR 3 | | | | | | | | Effluents | | | Infl. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Day | Date | COD mg/l | TKN mg/l | MLSS mg/l | VSS mg/l | DSVI ml/g | Sett ml/l | pH | OUR | peak DO | Aerob. % | COD mg/l | TKN mg/l | NO3 mg/l | NO3 mg/l |
| 210 | 1 | 557 | 54.6 | 2354 | 2056 | 314 | 740 | 7.63 | | | 0 | 54 | 13.9 | 2.34 | 7.636 |
| 211 | 2 | 536 | 54.6 | 2502 | 2160 | 328 | 820 | 7.66 | | | 0 | 71 | 24 | 0 | 8.291 |
| 212 | 3 | 523 | 58 | | | | | | 24.7 | 2.3 | 90 | 45 | 13.6 | 36.4 | 6.332 |
| 213 | 4 | 479 | 54.5 | | | | | | | | 0 | 49 | 1.5 | 29.9 | 6.32 |
| 214 | 5 | 529 | 50.2 | 2602 | 2256 | 338 | 880 | 7.77 | | | 0 | 91 | 23.9 | 0 | 10.67 |
| 215 | 6 | 535 | 50.7 | 2386 | 2060 | 355 | 848 | 7.52 | 22 | 2.3 | 90 | 69 | 13.6 | 24.96 | 12.65 |
| 216 | 7 | 633 | 56.3 | 2418 | 2088 | 347 | 840 | 7.51 | | 2.3 | 100 | 45 | 5.5 | 39.91 | |
| 217 | 8 | 608 | 103 | 2472 | 2140 | 320 | 792 | 7.52 | | 2.3 | 100 | 89 | 10.1 | 6.24 | |
| 218 | 9 | 389 | 59.8 | 2542 | 2220 | 362 | 920 | 7.83 | 37 | 2.3 | 100 | 69 | 4 | 67.99 | |
| 219 | 10 | 479 | 81.7 | | | | | | | 2.3 | 100 | 51 | 3.4 | 70.98 | |
| 220 | 11 | 629 | 96.5 | 2516 | 2150 | 397 | 1000 | 6.51 | | 2.3 | 100 | 77 | 4.3 | 77.74 | |
| 221 | 12 | 665 | 104 | | | | | | | 2.3 | 100 | 75 | 4.7 | 80.86 | |
| 222 | 13 | 657 | 97.6 | 2628 | 2306 | 350 | 920 | 6.2 | 36.8 | 2.3 | 100 | 65 | 3 | 81.9 | |
| 223 | 14 | | | 2840 | 2478 | 394 | 1120 | 7.52 | | 2.3 | 100 | | | | |
| 224 | 15 | 462 | 52.5 | 2430 | 2104 | 370 | 900 | 7.56 | 16 | 2.3 | 100 | 56 | 4.4 | 77.74 | |
| 225 | 16 | 507 | 49.5 | 2510 | 2210 | 351 | 880 | 7.6 | 16.2 | 2.3 | 100 | 44 | 3.7 | 53.3 | |
| 226 | 17 | 543 | 41.9 | | | | | | | 2.3 | 100 | 37 | 3.9 | 43.81 | |
| 227 | 18 | 517 | 38.6 | | | | | | | 2.3 | 100 | 46 | 3.8 | 46.28 | |
| 228 | 19 | 531 | 39.9 | 2348 | 2066 | 242 | 568 | 7.52 | 22.4 | 2.3 | 100 | 54 | 4.1 | 43.81 | |
| 229 | 20 | 513 | 33.9 | 2580 | 2242 | 124 | 320 | 7.66 | | 2.3 | 100 | 62 | 5.7 | 47.45 | |
| 230 | 21 | 527 | 34.9 | 2528 | 2202 | 75 | 189 | | 23.3 | 2.3 | 100 | 76 | 6.3 | 50.31 | |
| 231 | 22 | 539 | 41.1 | 2330 | 1992 | 72 | 169 | 7.69 | 20.8 | 2.3 | 100 | 58 | 6.6 | 50.31 | |
| 232 | 23 | 560 | 35.5 | 2234 | 1988 | 70 | 156 | 7.72 | | 2.3 | 100 | | | | |
| 233 | 24 | 562 | 42.6 | | | | | | | | | | | | |

# APPENDIX I

Steady State Data and COD Balances calculated for systems CFR 2 and CFR 3 operated during phase 3 of the investigation. The calculations are for the steady state periods during which the aeration cycle was less than 30 minutes or when the systems were continuously aerated or operated fully anoxic.

COD Balance Phase 3 Systems CFR 2 & 3

Q = 10 l/d
fcv = 1.48 mgCOD/mgVSS
Vp = 7.5 l
fn = 0.1 mgN/mgVSS
waste = 0.5 l/d

| Steady State Period | Day | to | Day | M(Sti) mg/d | M(Ste) mg/d | Mwaste mg/d | M(Oc) | M(Xv) wasted mg/d | M(Xv) mgVSS | Xv mg/l | COD Mass Balance |
|---|---|---|---|---|---|---|---|---|---|---|---|
| CFR 2 | | | | | | | | | | | |
| 1 | 0 | | 53 | 5114.6 | 441.1 | 1190.2 | 2642.3 | 804.2 | 12062.5 | 1608.3 | 83.6 |
| 2 | 54 | | 85 | 4741.0 | 487.1 | 1281.7 | 1754.4 | 866.0 | 12990.0 | 1732.0 | 74.3 |
| 3 | 86 | | 117 | 4962.4 | 471.4 | 1125.6 | 1837.9 | 760.5 | 11407.9 | 1521.0 | 69.2 |
| 4 | 118 | | 129 | 4954.0 | 513.0 | 1477.6 | 2608.4 | 998.4 | 14975.6 | 1996.8 | 92.8 |
| 5 | 182 | | 192 | 4830.0 | 545.5 | 1553.4 | 2569.7 | 1049.6 | 15744.0 | 2099.2 | 96.7 |
| 6 | 216 | | 220 | 5476.0 | 1144.0 | 1381.2 | 1064.3 | 933.3 | 13998.8 | 1866.5 | 65.5 |
| 7 | 221 | | 242 | 5255.3 | 956.8 | 1256.2 | 1802.2 | 848.8 | 12732.2 | 1697.6 | 76.4 |
| CFR 3 | | | | | | | | | | | |
| 8 | 0 | | 53 | 5114.6 | 467.4 | 1128.4 | 1777.1 | 762.4 | 11436.7 | 1524.9 | 65.9 |
| 9 | 133 | | 136 | 4890.0 | 360.0 | 1630.2 | 2818.7 | 1101.5 | 16522.5 | 2203.0 | 98.3 |
| 10 | 158 | | 166 | 5486.7 | 564.4 | 1420.4 | 2785.2 | 959.7 | 14395.7 | 1919.4 | 86.9 |
| 11 | 216 | | 225 | 5652.5 | 658.8 | 1637.1 | 2512.6 | 1106.1 | 16592.1 | 2212.3 | 85.1 |

Nitrogen Calculations

| Steady State Period | Day | to | Day | M(Nnd) mg/d | M(Nti) mg/d | M(Nni) mg/d | M(Nte) mg/d | M(Nne) mg/d | M(Nw) mg/d | N Mass Balance 100% An/Ae. | M(Nng) mg/d |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0 | | 53 | 239.0 | 451.1 | 200.4 | 44.7 | 287.3 | 80.4 | | 326.0 |
| 2 | 54 | | 85 | 358.8 | 493.8 | 174.7 | 46.0 | 177.1 | 86.6 | | 361.2 |
| 3 | 86 | | 117 | 340.6 | 557.7 | 155.1 | 61.9 | 234.3 | 76.1 | | 419.7 |
| 4 | 118 | | 129 | 0.0 | 548.5 | 0.0 | 37.3 | 426.3 | 99.8 | 96.5 | 426.3 |
| 5 | 182 | | 192 | 0.0 | 419.0 | 0.0 | 17.0 | 343.2 | 105.0 | 86.6 | 343.2 |
| 6 | 216 | | 220 | 372.1 | 794.0 | 127.5 | 432.1 | 24.0 | 93.3 | 59.6 | 0.0 |
| 7 | 221 | | 242 | 630.1 | 473.5 | 1211.5 | 442.3 | 581.4 | 84.9 | 103.2 | 0.0 |
| 8 | 0 | | 53 | 247.4 | 451.1 | 200.8 | 43.4 | 284.8 | 76.2 | | 331.4 |
| 9 | 133 | | 136 | 16.1 | 464.8 | 0.0 | 25.8 | 312.8 | 110.2 | 105.1 | 328.9 |
| 10 | 158 | | 166 | 0.0 | 577.4 | 0.0 | 28.0 | 466.4 | 96.0 | 97.2 | 466.4 |
| 11 | 216 | | 225 | 24.2 | 813.3 | 0.0 | 49.3 | 629.2 | 110.6 | 103.9 | 653.4 |

| Period | M(Otm) | OUR mgO/l/h | %Aerob | M(Od) | M(On) |
|---|---|---|---|---|---|
| 1 | 3448.4 | 56.6 | 0.3 | 683.7 | 1489.8 |
| 2 | 2379.1 | 45.9 | 0.3 | 1026.2 | 1650.8 |
| 3 | 2782.1 | 47.7 | 0.3 | 974.0 | 1918.2 |
| 4 | 4556.6 | 25.3 | 1.0 | 0.0 | 1948.2 |
| 5 | 4138.0 | 23.0 | 1.0 | 0.0 | 1568.3 |
| 6 | 0.0 | 22.9 | 0.0 | 1064.3 | |
| 7 | 0.0 | 23.0 | 0.0 | 1802.2 | |
| 8 | 2583.9 | 45.7 | 0.3 | 707.7 | 1514.5 |
| 9 | 4248.0 | 23.6 | 1.0 | 0.0 | 1429.3 |
| 10 | 4916.6 | 27.3 | 1.0 | 0.0 | 2131.3 |
| 11 | 5388.0 | 29.9 | 1.0 | 0.0 | 2875.4 |